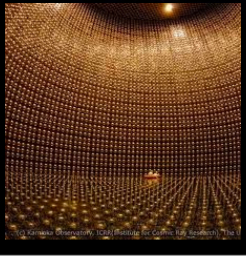
Physics Potential of a Future Large ν Detector in Korea

Sunny Seo

Neutrino Division
Fermilab

Neutrino Seminar
Fermilab



(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The U

2023.10.19

Physics Potential of a Few Kiloton Scale Neutrino Detector at a Deep Underground Lab in Korea

Seon-Hee Seo,*[5], Jose Alonso[11], Pouya Bakhti[8], Janet Conrad[11], Steve Dye[4], Doojin Kim[14], Jost Migenda[9], Marco Pallavicini[7], Jong-Chul Park[3, 6], Meshkat Rajaee[8], Mike Shaevitz[2], Seodong Shin[6, 8], Joshua Spitz[13], Daniel Winklehner[11], Slawomir Wronka[12], Michael Wurm[10], Minfang Yeh[1]

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arXiv:2309.13435

Outline

- Introduction to Yemilab

  --Large Neutrino Detector, a.k.a. LSC

- LSC Physics Program and Potentials
  1. Solar/Geo/Supernova Burst ν
  2. Dark photon Search
  3. Sterile Neutrino Search

LSC:
Liquid **S**cintillation **C**ounter

Yemilab @ Handuk Iron Mine

- The 1st deep underground lab dedicated to science in Korea

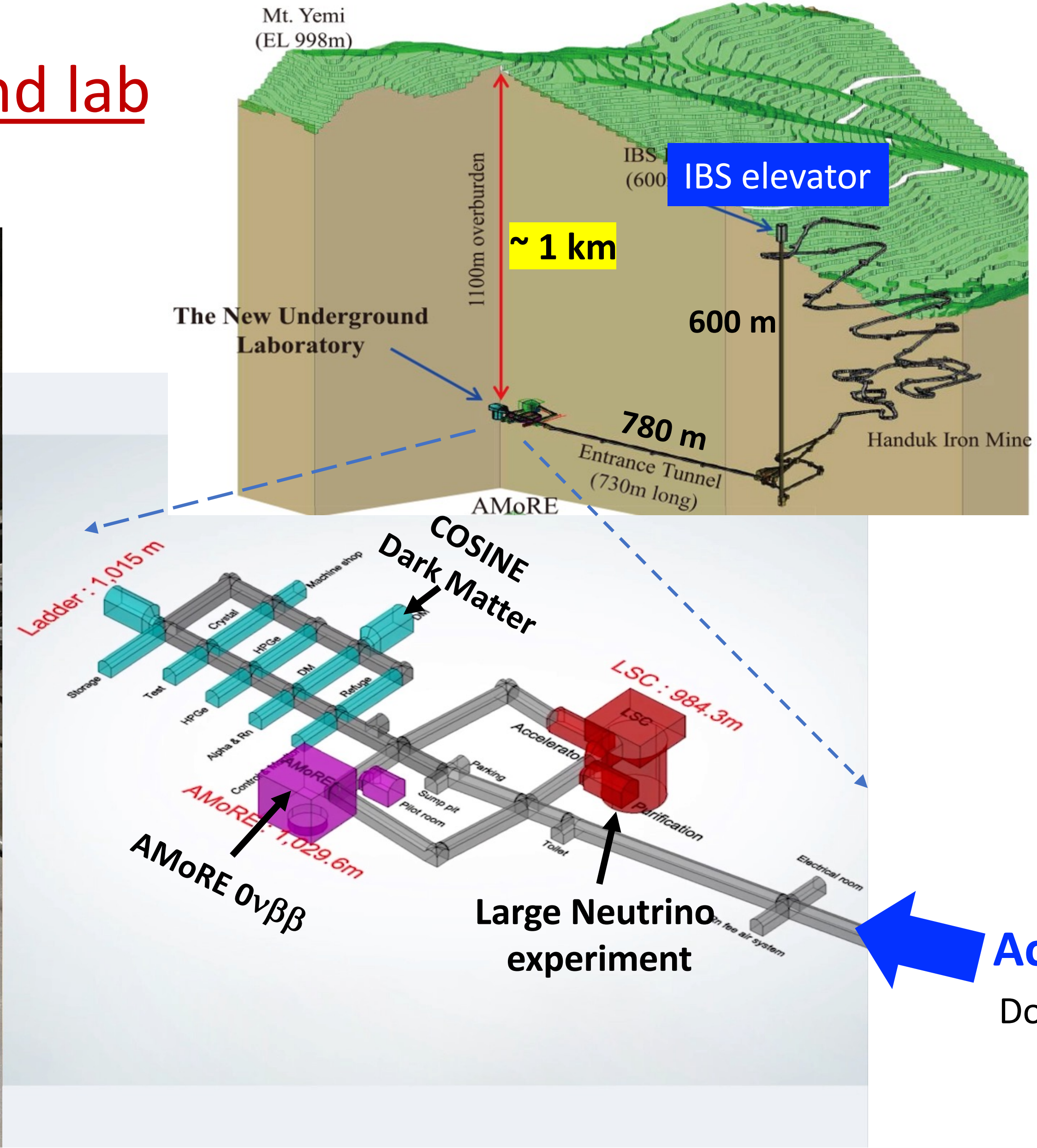
Handuk Iron Mine @Jeongsun

IBS elevator

Yemi underground lab

~1 km depth

Access Tunnel



IBS elevator

~ 1 km

600 m

780 m

COSINE
Dark Matter

AMoRE 0νββ

Large Neutrino
experiment

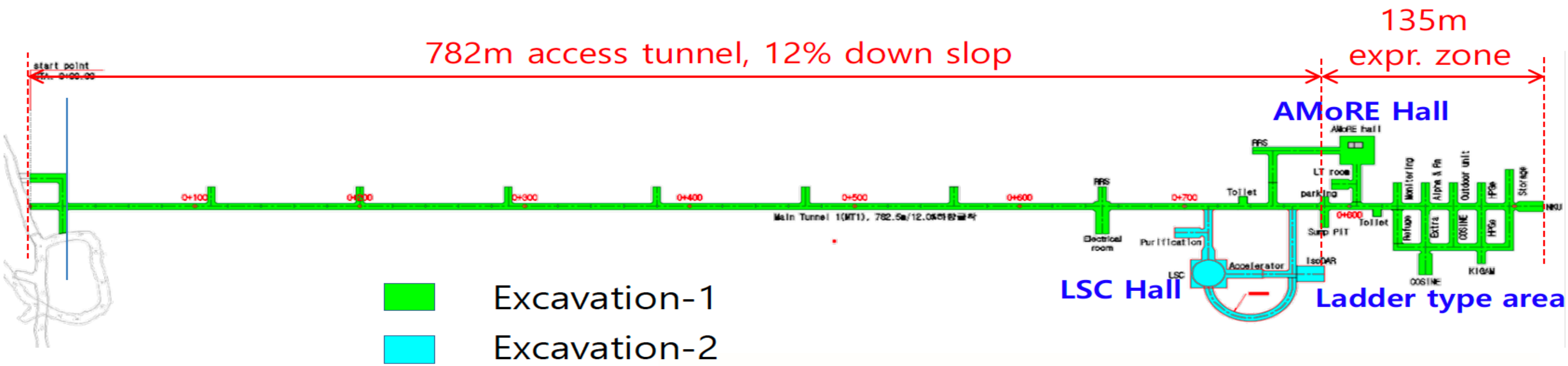
Access Tunnel

Down Slope: 12%

❖ Yemilab Construction (2017.09 – 2022.09, 60 months)

K.S. Park
@Yemilab Workshop

- Yemilab construction had two steps
- 1st construction (2017.09 – 2020.08) 35 months
  - Tunnel excavation : 70% of whole Yemilab volume
  - Building cage system
  - Purchase of surface office building
- 2nd construction (2021.06 – 2022.09) 15 months
  - LSC tunnel excavation : 30% of whole Yemilab volume
  - Electricity, machinery, refuge, toilets
  - Hoist, detector room, clean rooms for AMoRE-II
  - Renovation of surface office



❖ Media Coverage on “Yemilab Opening”

기초과학연구원, 암흑물질탐색·중성미자 연구 2023년부터 본격 실험

2022-10-05
오상미 기자 osm@mtnews.net

▲ 강원도 정선군 예미랩 지상연구실에서 5일(수) 기초과학연구원(IBS) 예미랩 준공식이 개최됐다.

[기계신문] 과학기술정보통신부(이하 ‘과기정통부’)와 기초과학연구원(IBS)은 5일(수) 강원도 정 … 에서
예미랩 준공식을 개최했다.

한경 IT·과학

지하 1100m 어둠 속에서 '우주 암흑물질의 비밀' 푼다

이해성 기자

입력 2022.08.11 16:54 수정 2022.08.12 05:42 지면 A14

IBS, 세계적 연구기관 도약

기초과학硏 '예미랩' 내달 준공
강원도 철광 지하에 연구시설

은하의 근원 '암흑물질' 규명 도전

오늘의 주요뉴스

[단독] 지하 1km 아래 '거대 실험실'…그곳에 우주 비밀이 있다

중앙일보 | 입력 2022.08.19 10:50 업데이트 2022.08.19 16:40

최준호 기자 구독

[최준호의 첨단의 끝을 찾아서]IBS 지하실험연구단 정선 예미랩

우주의 수수께끼 풀러 1000m 땅속으로 들어가다

이근영 기자 + 구독

Oct. 5th, 2022

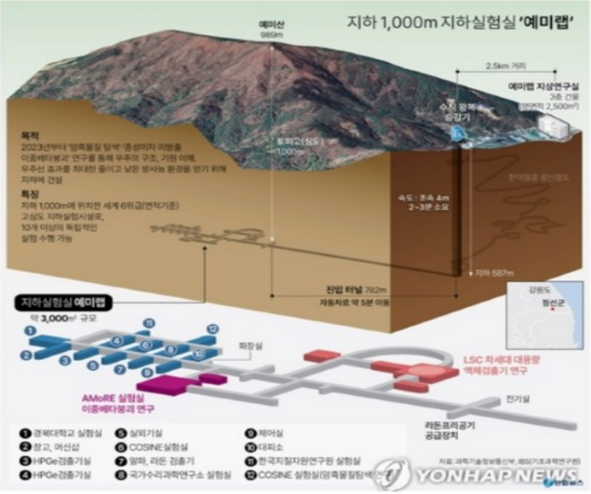
동아사이언스

과학

강원 정선 지하 1000m에서 우주 비밀 밝힌다

2022.10.05 14:00

| 기초과학연구원 고심도 지하실험시설 '예미랩' 5일 준공



과기부·기초과학연, 세계 6위 규모 지하실험실 '예미랩' 준공

기사입력 : 2022년10월05일 15:34 | 최종수정 : 2022년10월05일 15:34

가 + 가 - 프린트

5일 강원도 정선군서 준공식 개최
기존 실험실 10배·세계 6위 규모

YouTube 팝콘뉴스TV

이웃과 함께하는
팝콘뉴스

#이웃공동체 #상생경제 #MZ열전 #오피니언

우오현 SM그룹 회장 "세계 최초 암흑물질 발견 위해 적극 협력"

SM한덕철광산업, 정선 '예미랩 지하실험실' 완공

정찬혁 기자 (hyuck277@daum.net) | 기사입력 2022/10/07 [13:43]

The 1st Yemilab Workshop

Oct.15-18, 2022

Oct 15 – 18, 2022
High-1 Resort, Grand Hotel Convention Tower 5th floor
Asia/Seoul timezone

https://indico.ibs.re.kr/event/531/

This is a Hybrid Workshop. Registered participatns will get ZOOM connection info.

- Overview
- Timetable
- Contribution List
- Registration
- Participant List
- Venue
- Accommodation
- Meals and Banquet
- Gondola and Hiking
- LOC
- Covid Situation
- Visa & Entrance to Korea

Contact

sunny.seo@ibs.re.kr

Welcome to the 1st Yemilab Workshop!

Yemilab is the first deep underground lab dedicated to science in Korea and its construction was successfully finished recently. To celebrate the kick-off of the Yemilab, we are organizing this workshop and cordially invite world experts in underground physics. New ideas, technologies, or perspectives will be shared in this workshop.

Anyone who is curious or excited about Yemilab is very welcome to join us!

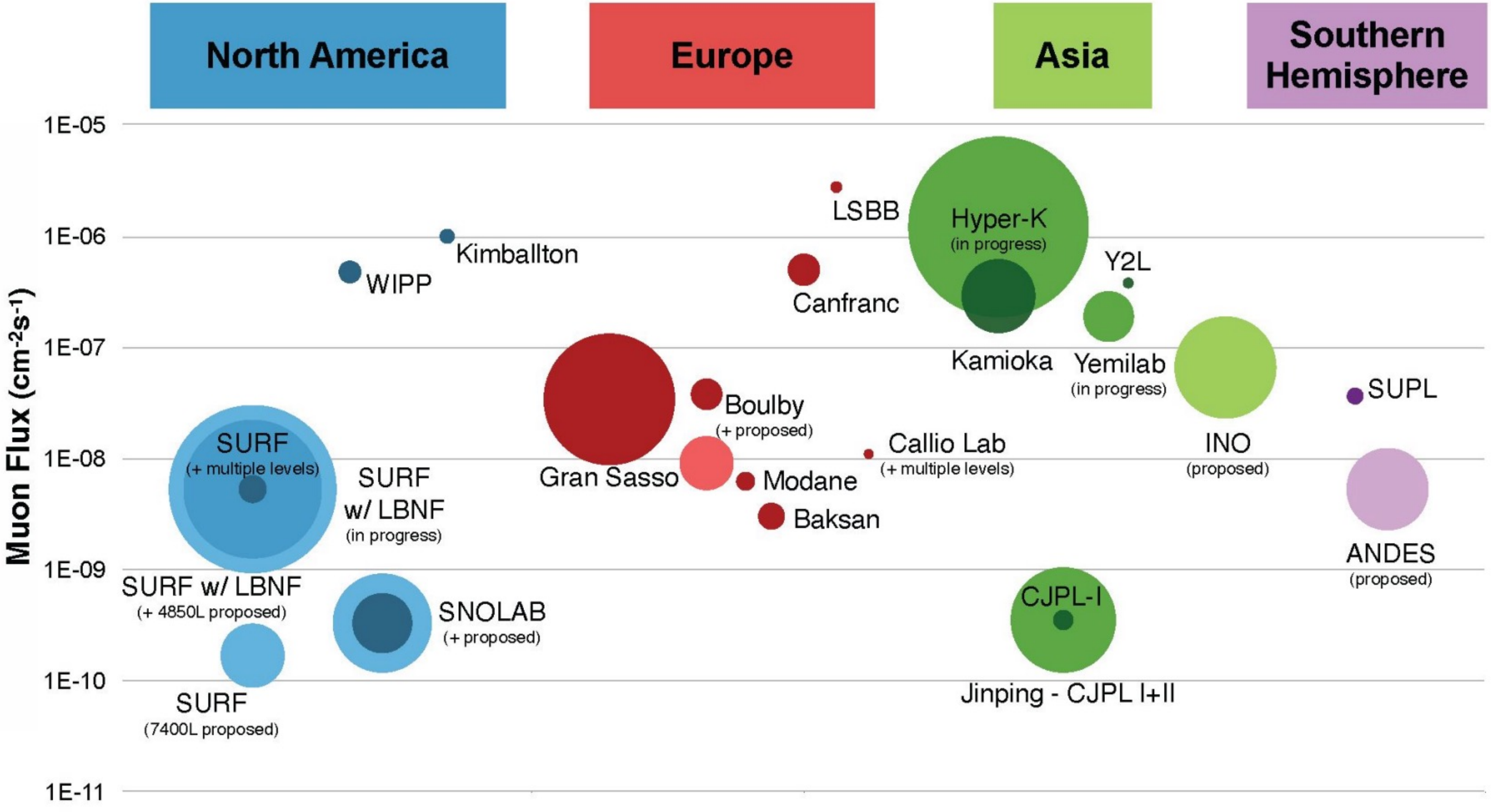
No registration fee.

Free meals for all in-person participants who register **by Oct. 6 (Th)**.

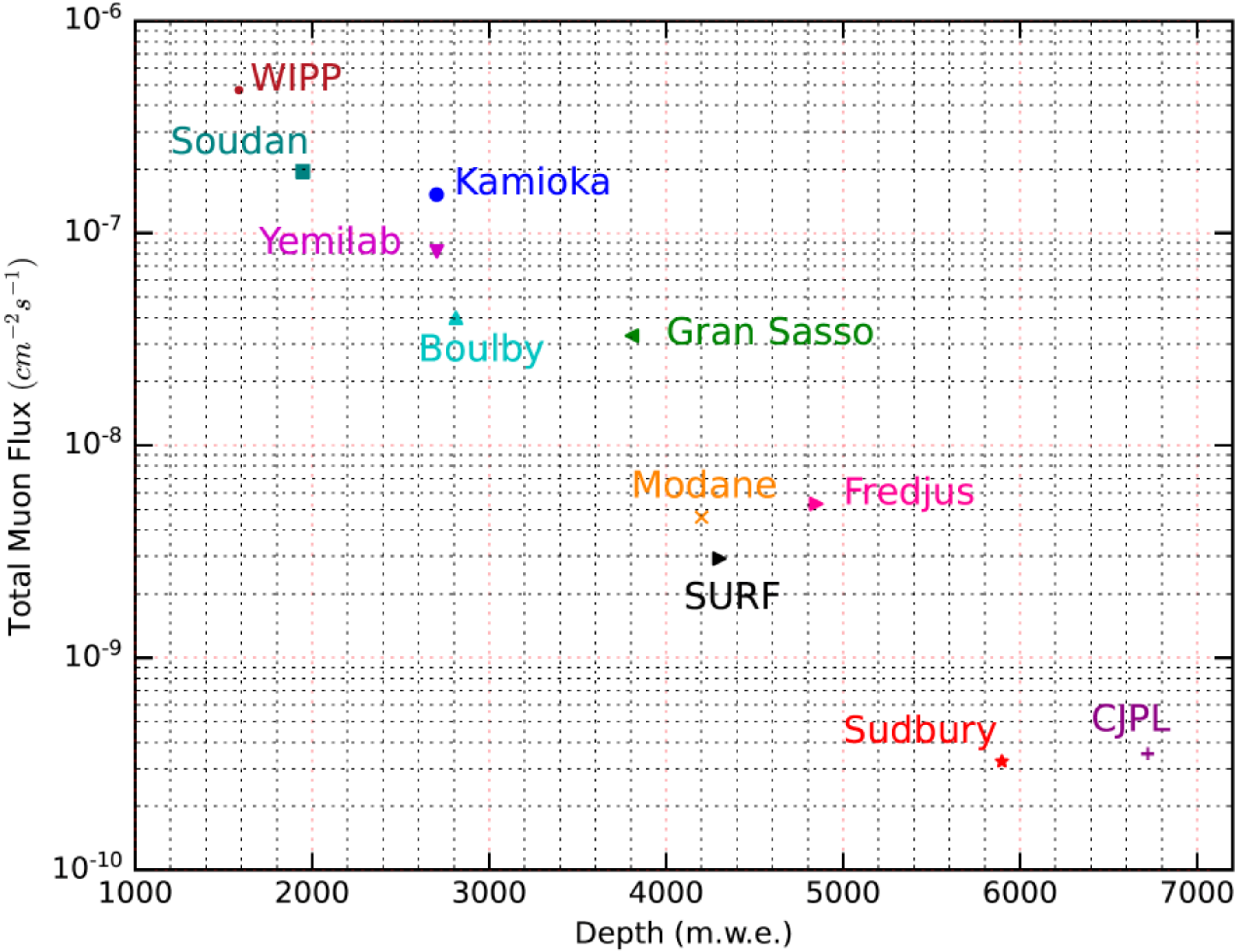
- 10/15 (Sat): Arrival, Registration, Reception
- 10/16 (Sun): Yemilab Tour
- 10/17(M)-18(Tu): Physics Workshop, Banquet

World Underground Labs

- ❑ **Yemilab** is the **6th** largest underground lab in the world.



Muon Flux Comparison



~86 muons /m^2/day

< 1 muons /m^2/day

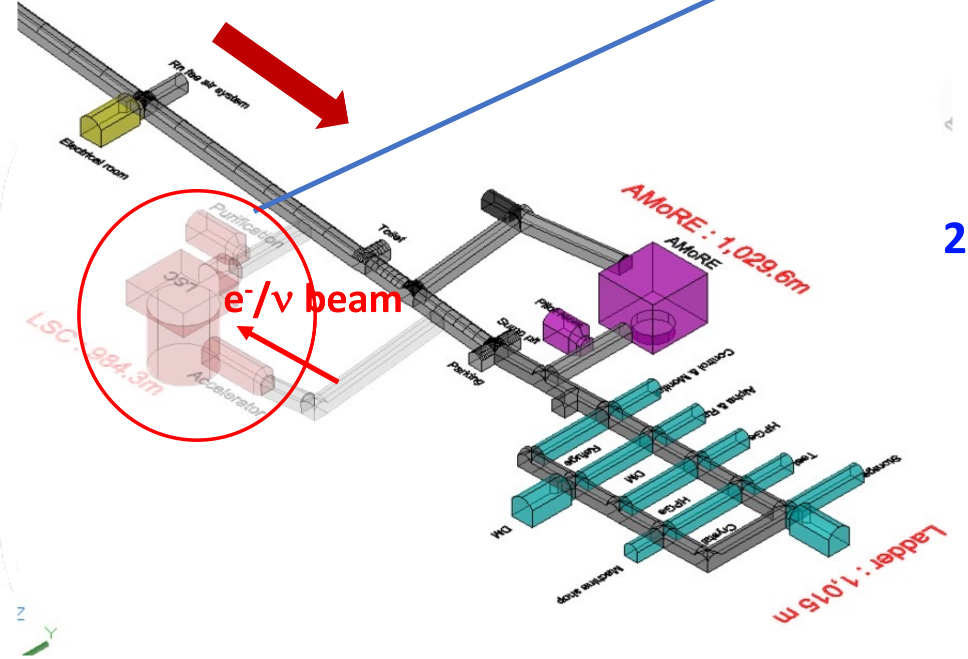
Large ν Detector (LSC) @Yemilab

LSC = Liquid Scintillation Counter

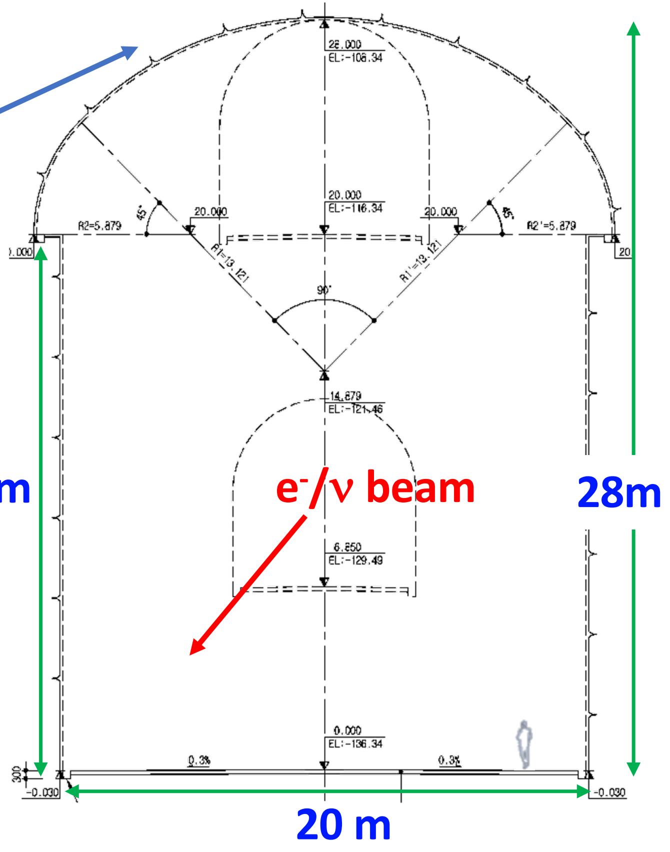
LSC Pit: 20 m (D) x 20 m (H)

LSC Hall construction:
June 2021 – Feb. 2022

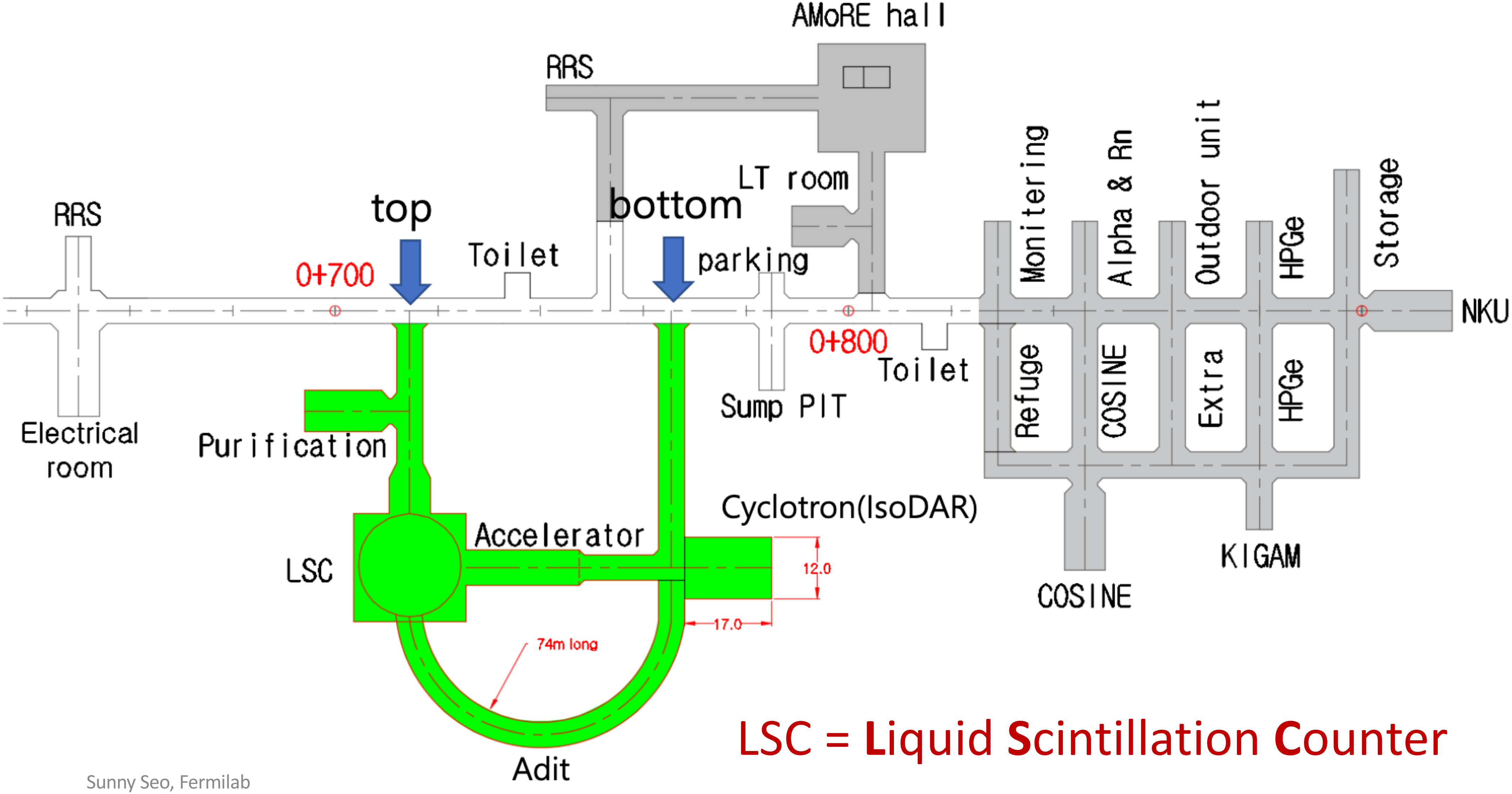
Tunnel entrance



LSC Hall

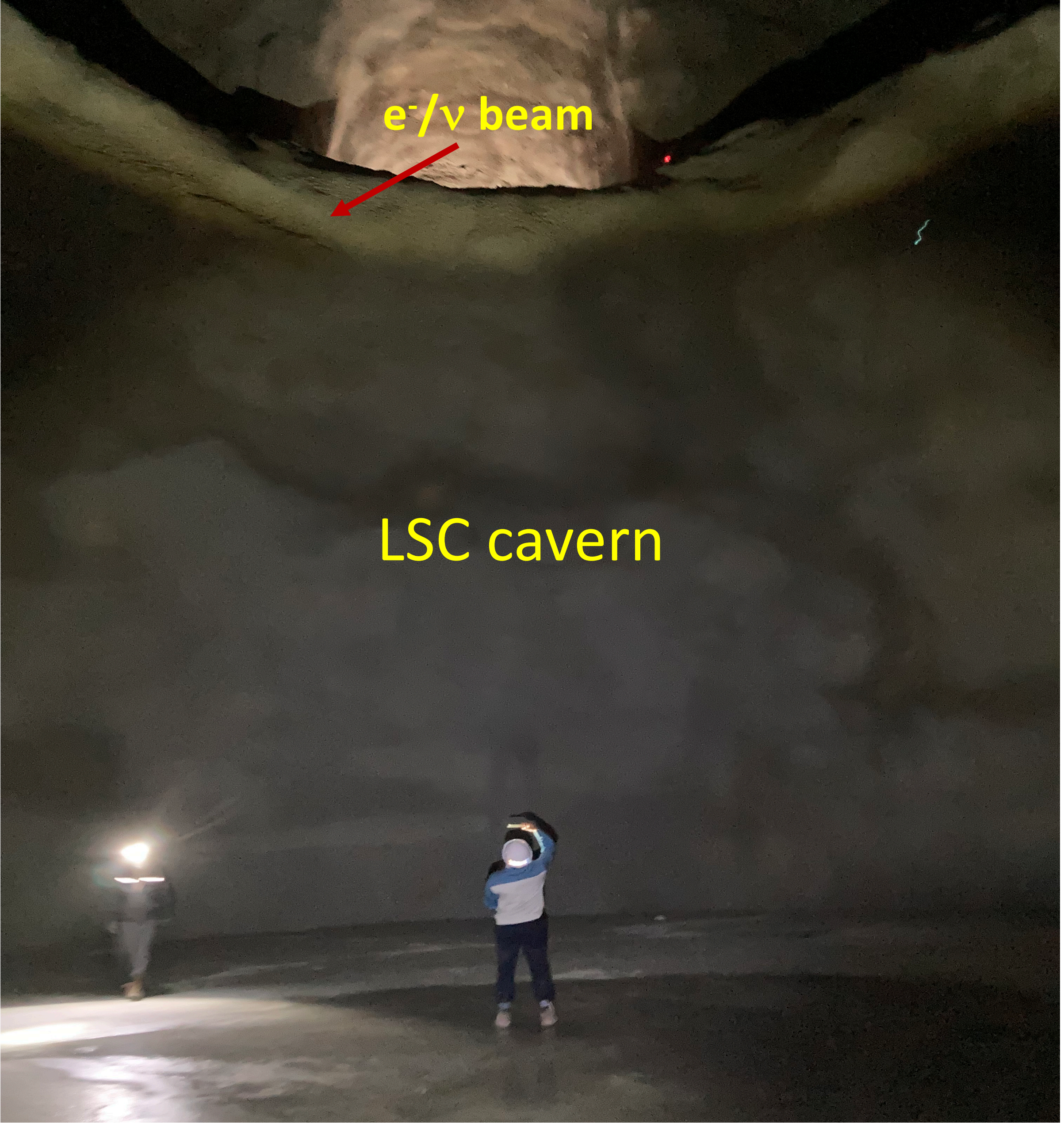


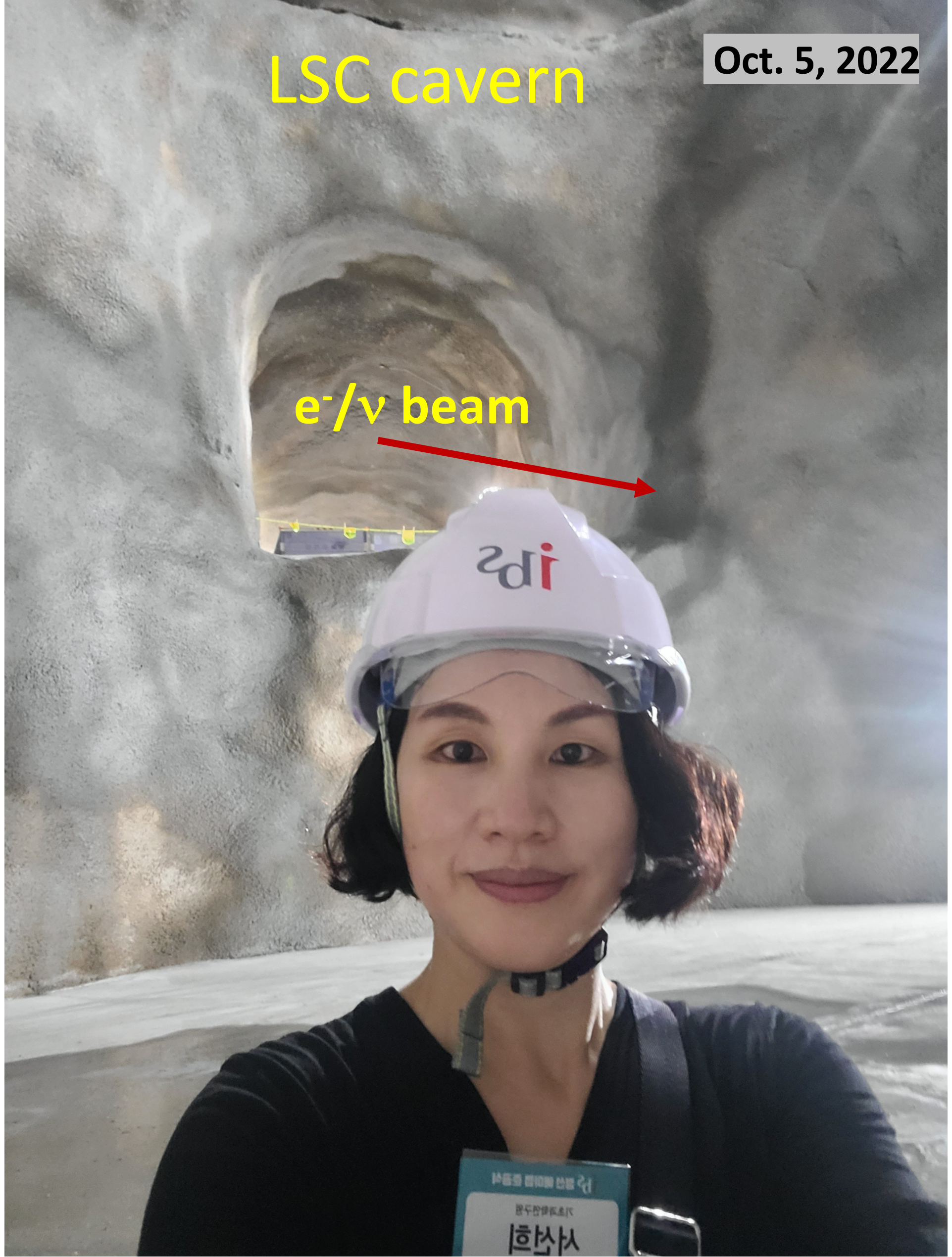
❖ Yemilab Layout (Top view)



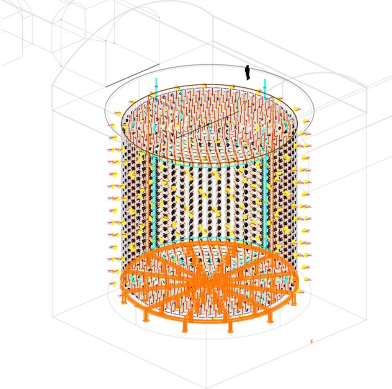
LSC = **L**iquid **S**cintillation **C**ounter

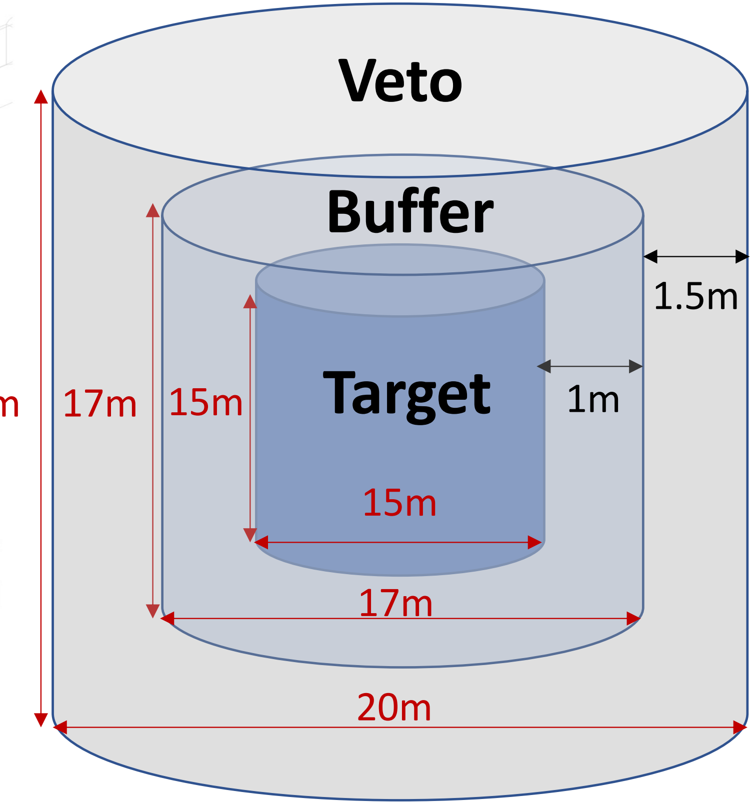
Sunny Seo, Fermilab

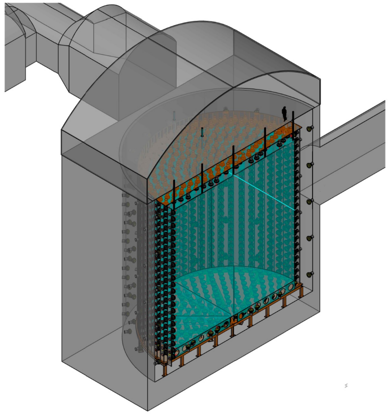

e^-/ν beam
LSC cavern


LSC cavern
Oct. 5, 2022
e^-/ν beam

Candidate Detector Design



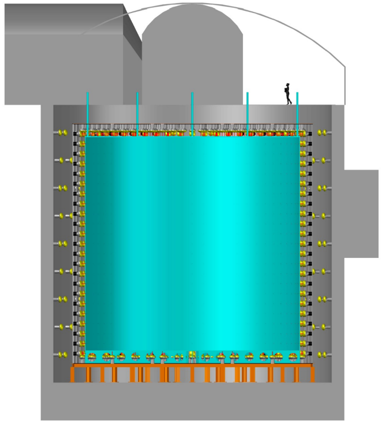




Target: **2.26 kton LS**

Buffer: 1.14 kton mineral oil

Veto: 2.41 kton water



1200(1800,2400) x 20 inch PMTs = 20% (30, 40)% coverage

Why LS Detector?

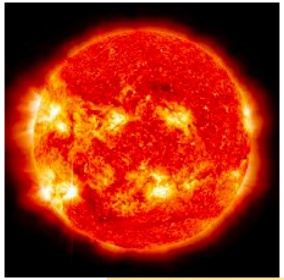
- ❑ Light yield of LS is high.

→Good energy resolution, low energy threshold
→Good for physics at O(1~10 MeV)

- ✓ Discovery of neutrino in 1956 was done using LS detector by **Reines and Cowan**'s team.
- ✓ θ_{13} in PMNS matrix was discovered using LS detectors in 2012 by **Daya Bay & RENO**.
- ✓ Many sterile neutrino search experiments using reactor ν use LS detector (**NEOS, PROSPECT, STEREO** etc).
- ✓ **Borexino** solar ν experiment used LS detector.
- ✓ **JUNO** is a LS detector to determine ν mass ordering.

Broad Physics Program

Solar ν

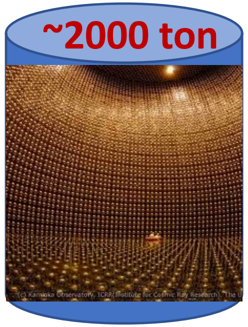


Supernova ν

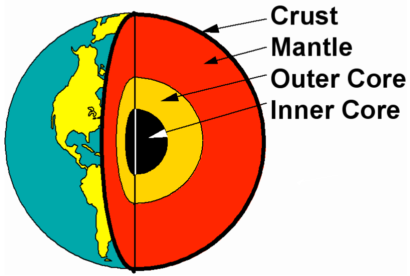
ν Telescope

e- beam

Dark Photon

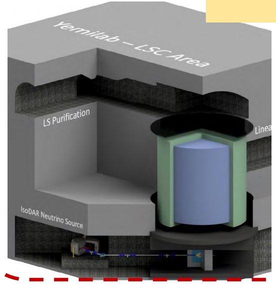


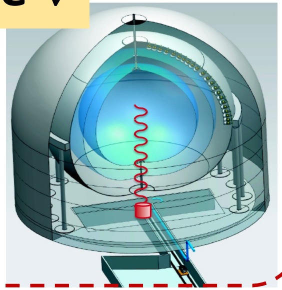
Geo ν



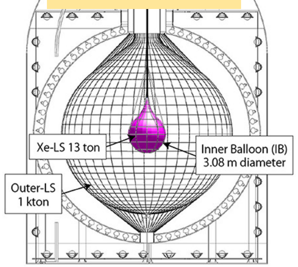
New step to Geo Science

Sterile ν





0νββ ?

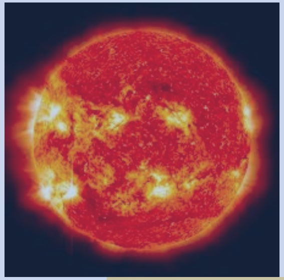


Broad Physics Program

Phase-I

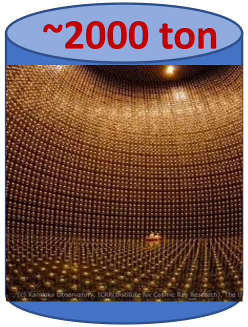
Detector alone

Solar ν



Supernova ν

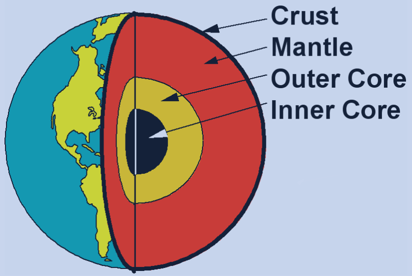
ν Telescope



e- beam

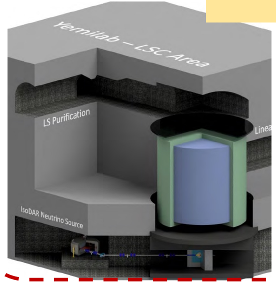
Dark Photon

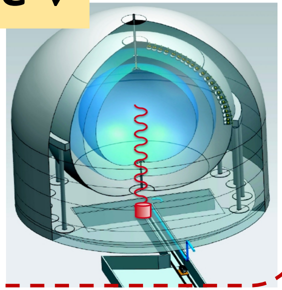
Geo ν



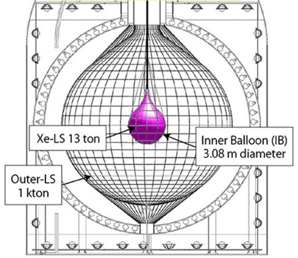
New step to Geo Science

Sterile ν

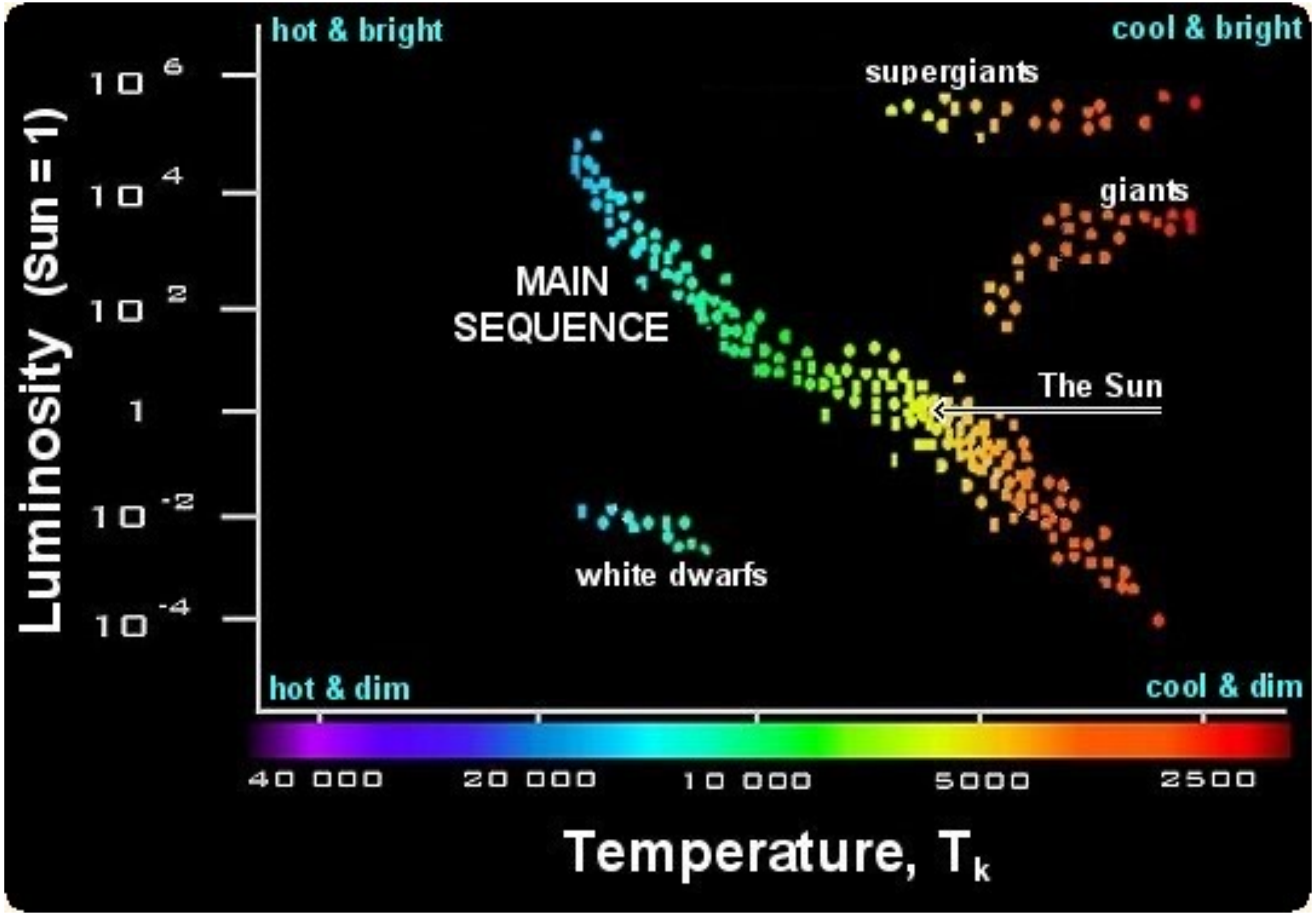




0νββ ?



Hertzsprung-Russell Diagram



❖ Main Sequence Stars

- Hot → Bright
- Cool → Dim
- ~90% stars in universe

➢ Understanding the Sun would provide important insights to understand Main Sequence Stars.

Solar Neutrino Production

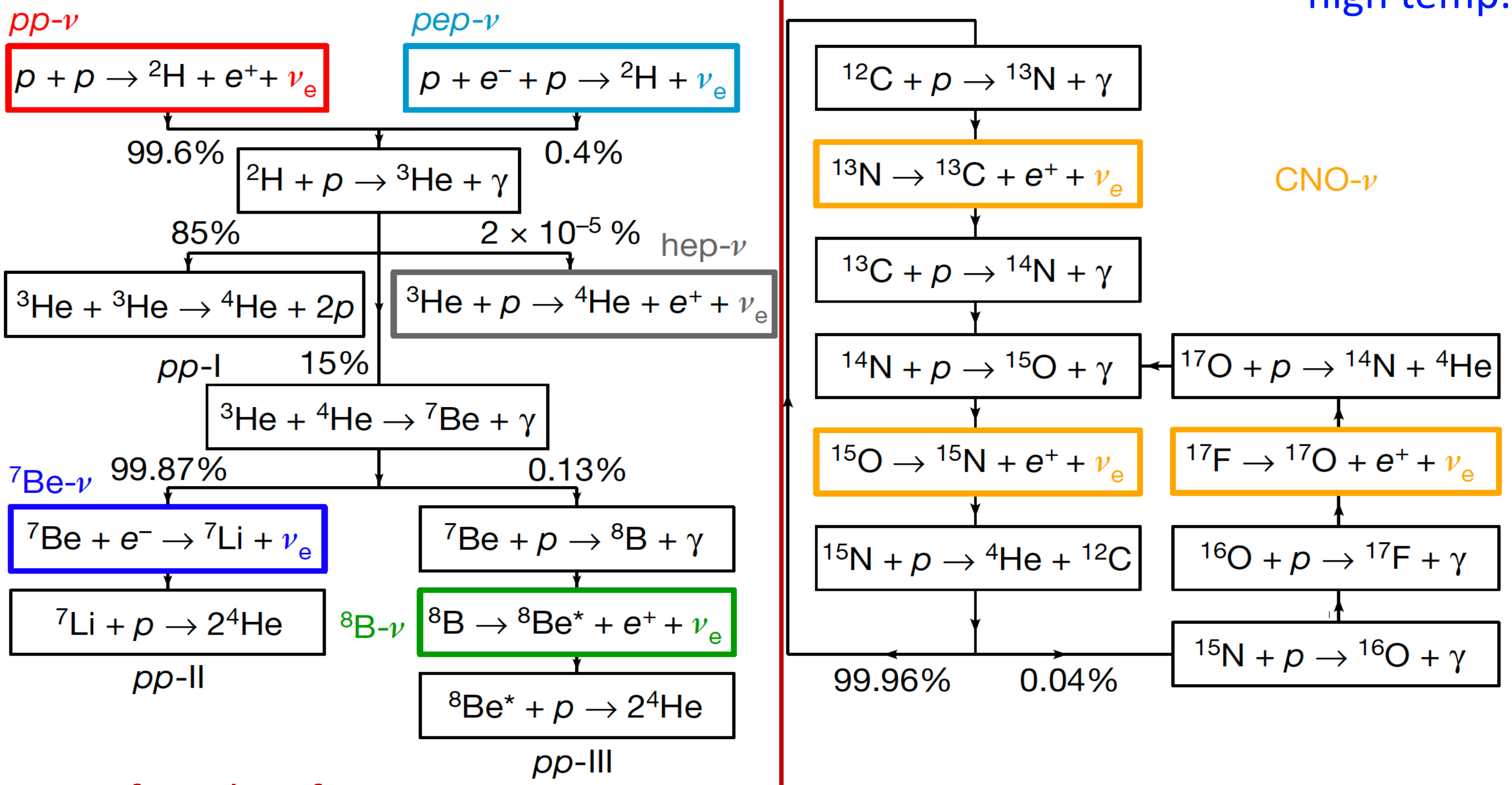
99%

PP chain

Main process for low temp. star

CNO cycle

Main process for high temp. star



pp-ν

$p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu_e$

pep-ν

$p + e^- + p \rightarrow {}^2\mathrm{H} + \nu_e$

99.6%

0.4%

${}^2\mathrm{H} + p \rightarrow {}^3\mathrm{He} + \gamma$

85%

2×10^{-5} %

hep-ν

${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p$

${}^3\mathrm{He} + p \rightarrow {}^4\mathrm{He} + e^+ + \nu_e$

pp-I

15%

${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$

^{7}Be-ν

99.87%

0.13%

${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$

${}^7\mathrm{Be} + p \rightarrow {}^8\mathrm{B} + \gamma$

${}^7\mathrm{Li} + p \rightarrow 2\,{}^4\mathrm{He}$

^{8}B-ν

${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be}^* + e^+ + \nu_e$

pp-II

${}^8\mathrm{Be}^* + p \rightarrow 2\,{}^4\mathrm{He}$

pp-III

${}^{12}\mathrm{C} + p \rightarrow {}^{13}\mathrm{N} + \gamma$

${}^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + e^+ + \nu_e$

CNO-ν

${}^{13}\mathrm{C} + p \rightarrow {}^{14}\mathrm{N} + \gamma$

${}^{14}\mathrm{N} + p \rightarrow {}^{15}\mathrm{O} + \gamma$

${}^{17}\mathrm{O} + p \rightarrow {}^{14}\mathrm{N} + {}^4\mathrm{He}$

${}^{15}\mathrm{O} \rightarrow {}^{15}\mathrm{N} + e^+ + \nu_e$

${}^{17}\mathrm{F} \rightarrow {}^{17}\mathrm{O} + e^+ + \nu_e$

${}^{15}\mathrm{N} + p \rightarrow {}^4\mathrm{He} + {}^{12}\mathrm{C}$

${}^{16}\mathrm{O} + p \rightarrow {}^{17}\mathrm{F} + \gamma$

${}^{15}\mathrm{N} + p \rightarrow {}^{16}\mathrm{O} + \gamma$

99.96%

0.04%

Solar ν: ~3% of total E of Sun

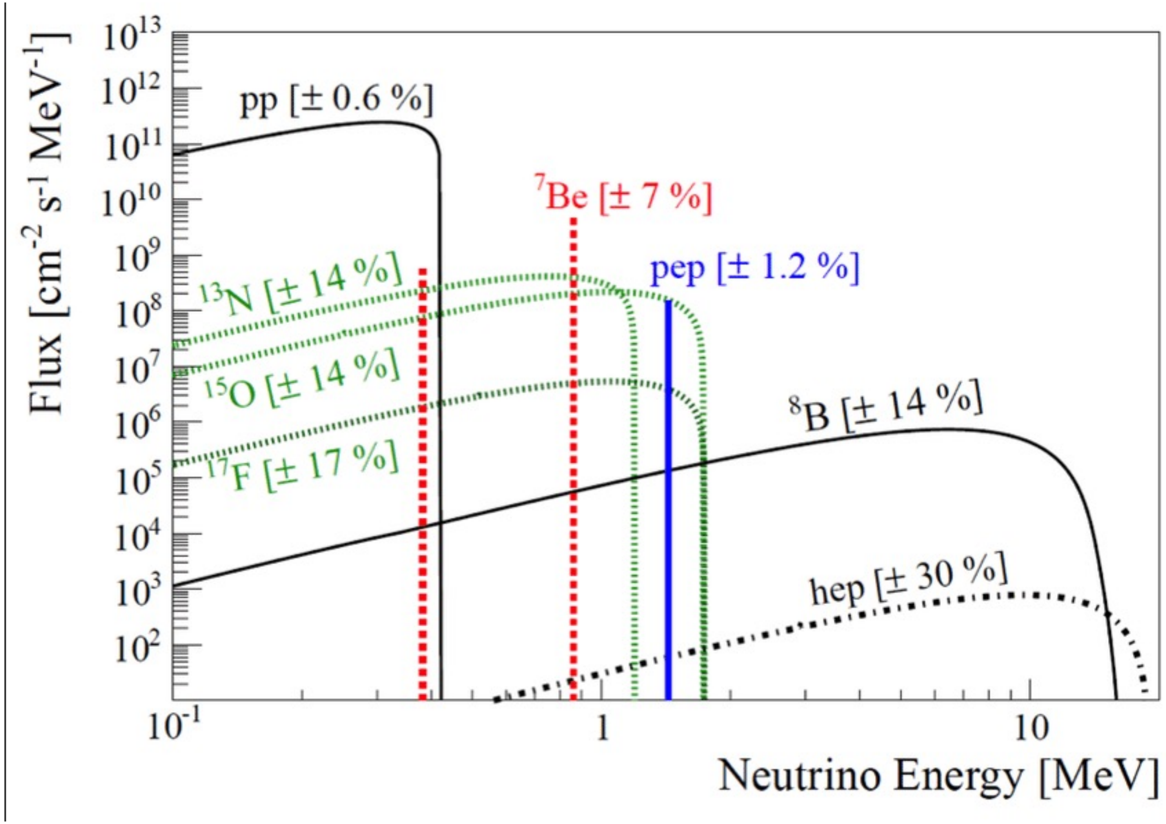
Borexino (Nature, 2018)

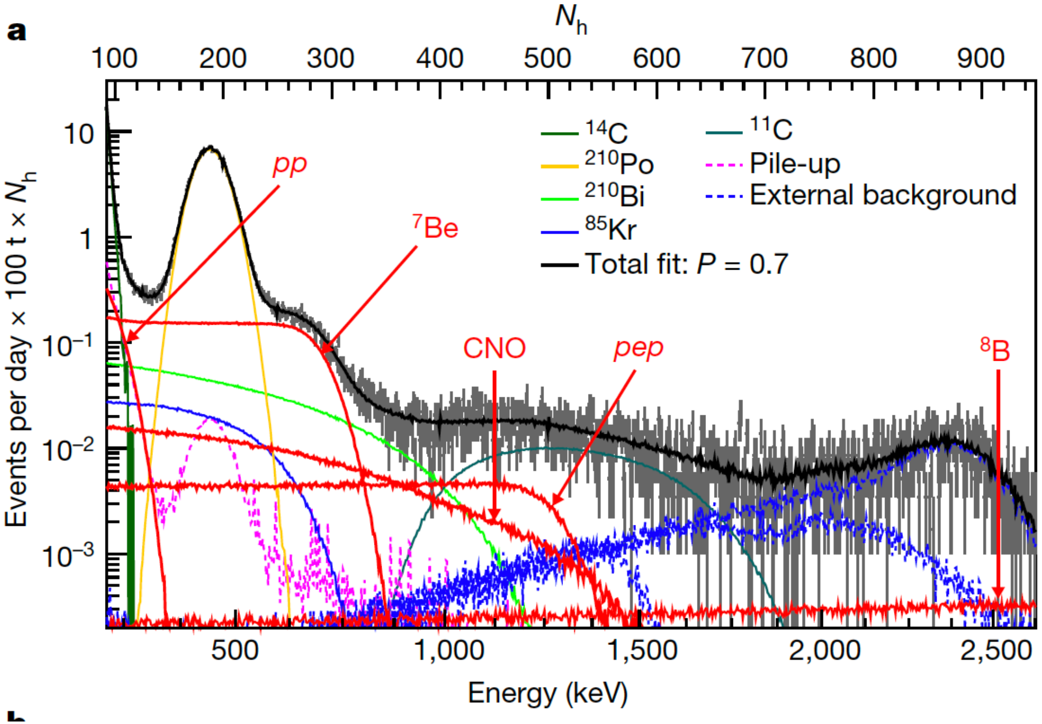
Solar neutrino spectra

Expected

Observed

$\nu_e + e^- \rightarrow \nu_e + e^-$



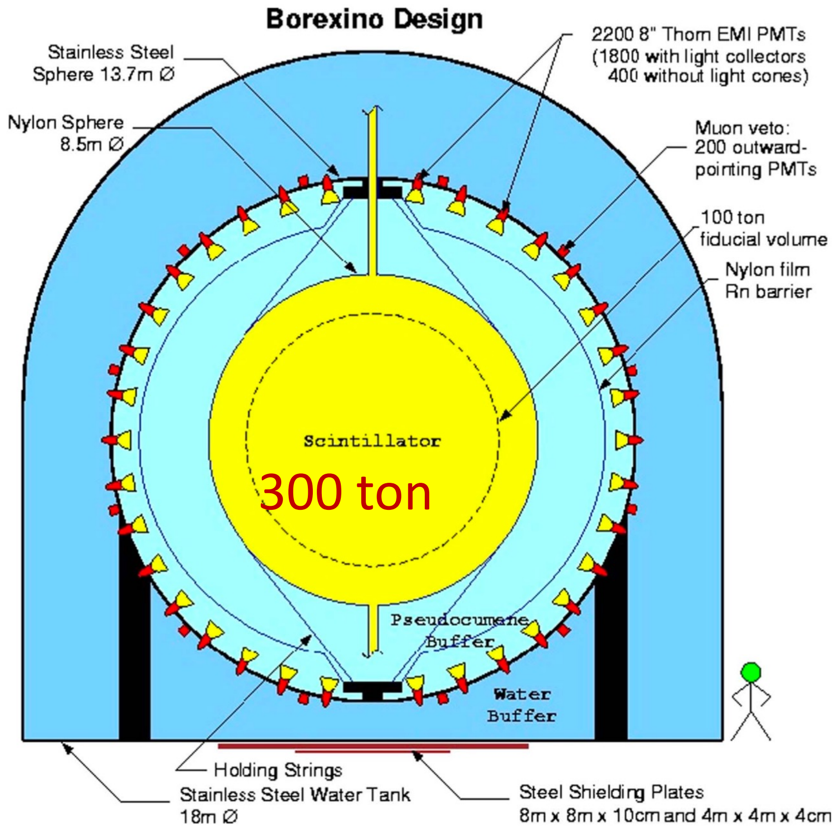


@Borexino

~70 billion solar ν/cm²/sec @Earth

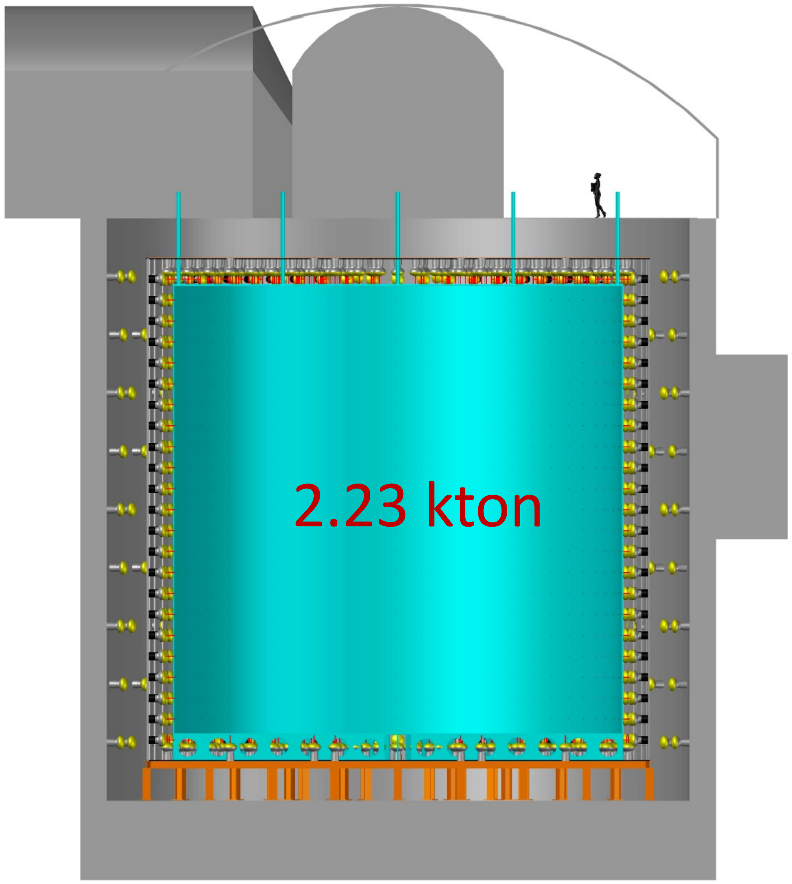
Solar ν Experiment

Borexino (2007-2021)



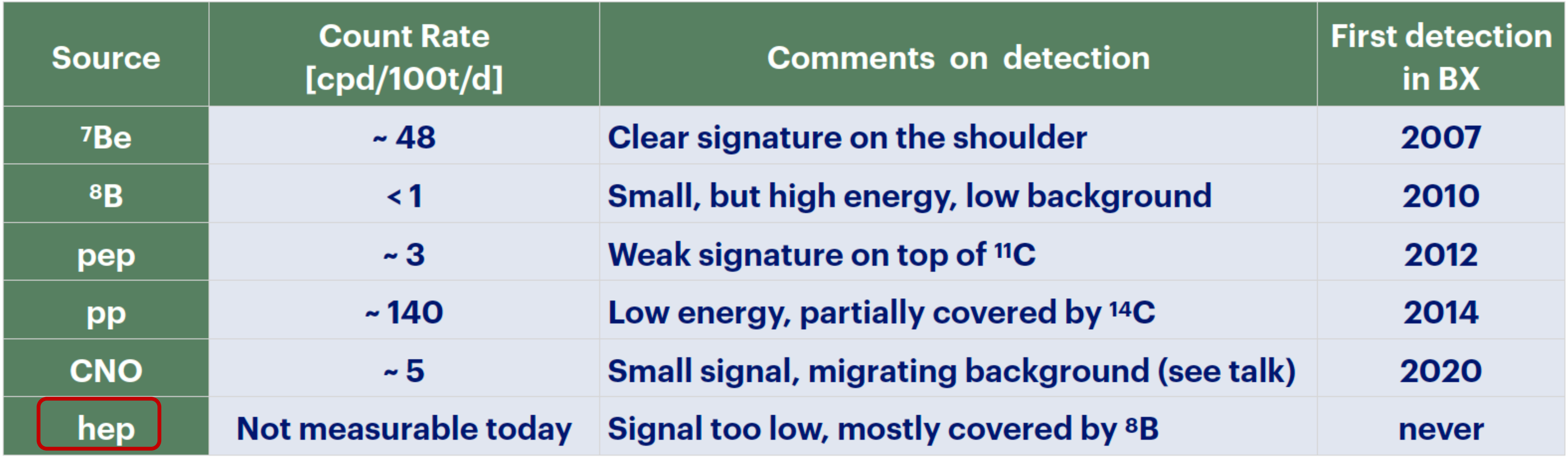
x 8

LSC



❖ Borexino Solar Neutrino Measurements

Borexino (Nature, 2018)

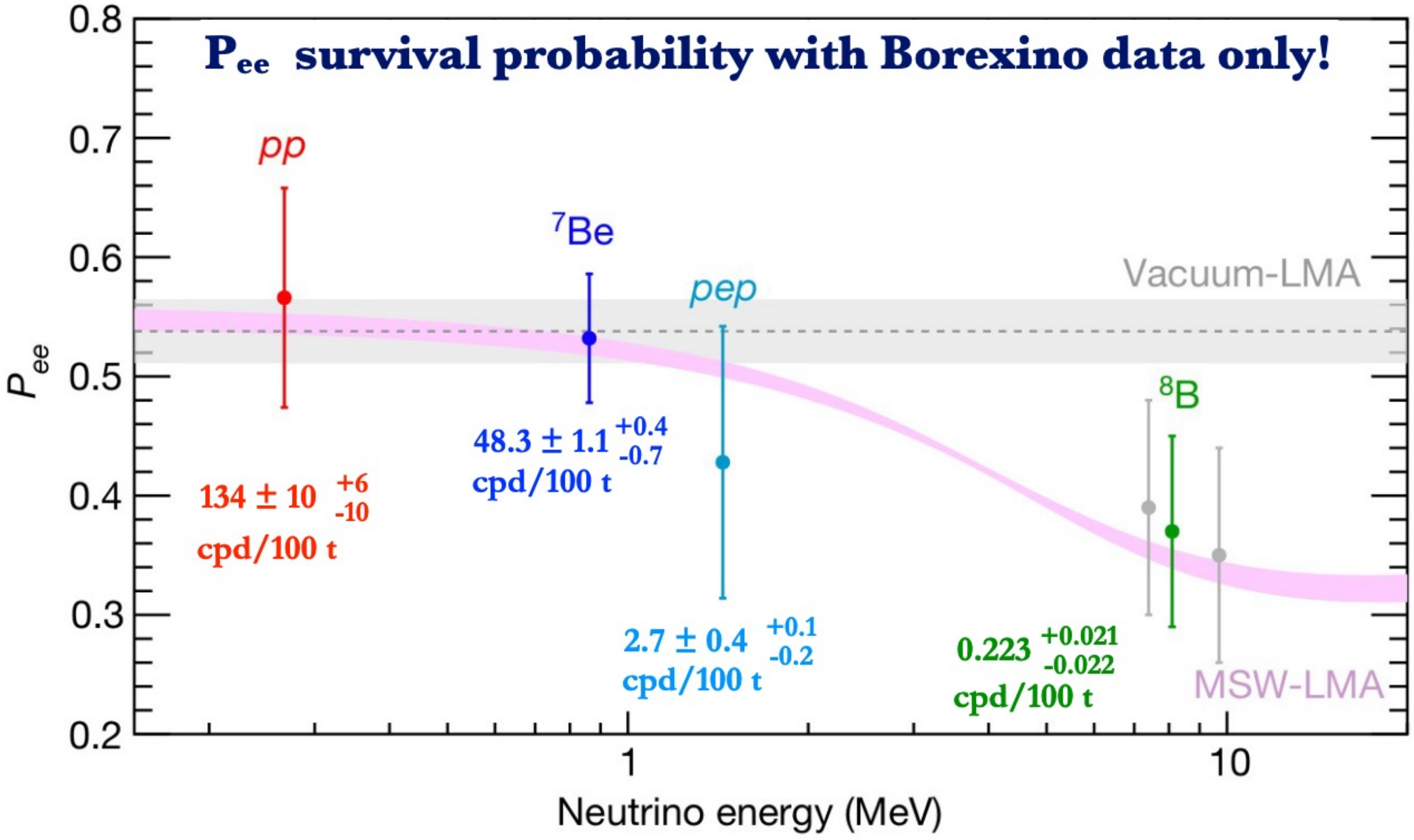


Source	Count Rate [cpd/100t/d]	Comments on detection	First detection in BX
^{7}Be	~ 48	Clear signature on the shoulder	2007
^{8}B	< 1	Small, but high energy, low background	2010
pep	~ 3	Weak signature on top of ^{11}C	2012
pp	~ 140	Low energy, partially covered by ^{14}C	2014
CNO	~ 5	Small signal, migrating background (see talk)	2020
hep	Not measurable today	Signal too low, mostly covered by ^{8}B	never

→ So far, Borexino is the only experiment which measured all types of solar ν except ***hep*** ν.

❖ Borexino Solar Neutrino Measurements

Borexino (Nature, 2018)



Comprehensive chain:
Nature 562 (2018) 7728, 505.
Phys. Rev. D (2019)

pp:
Nature 512 (2014) 7515, 383.

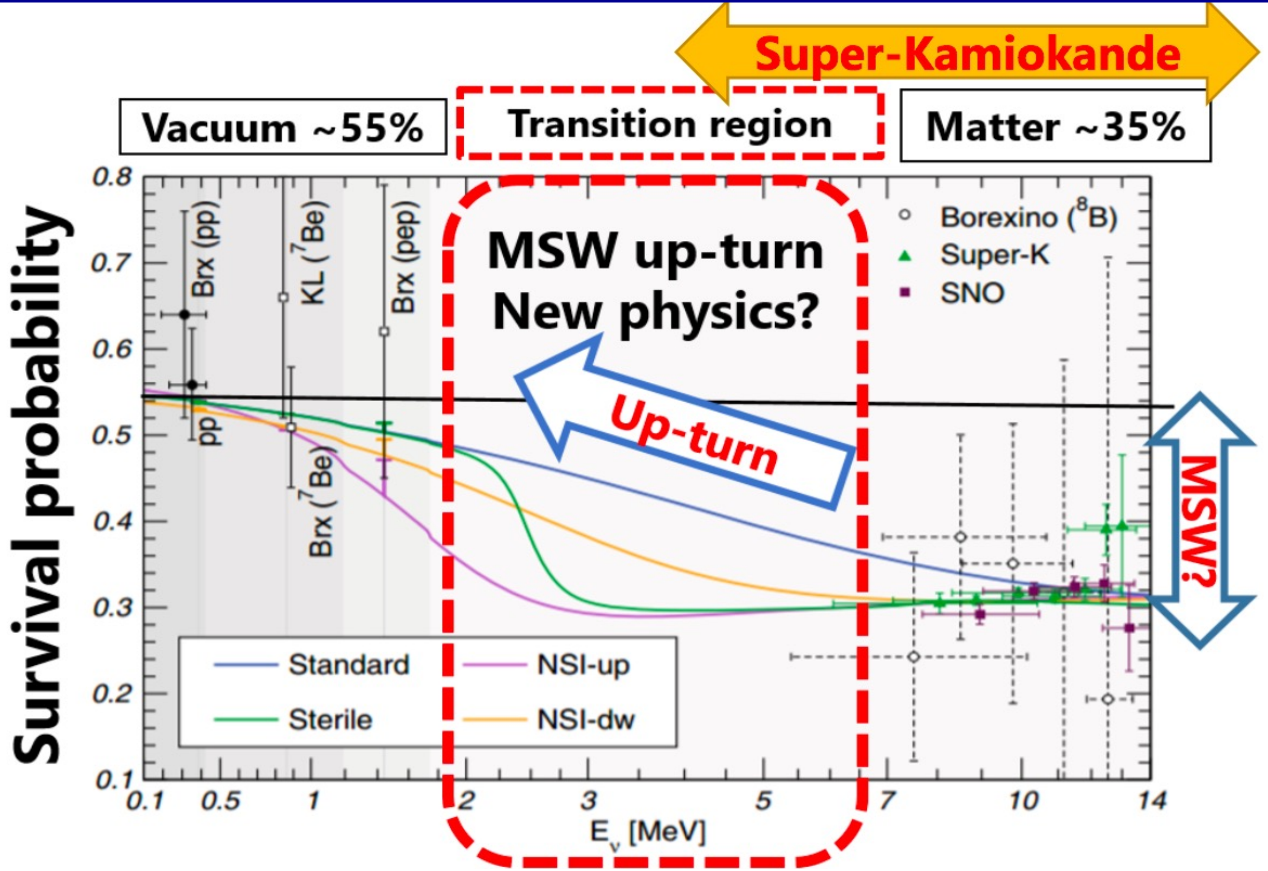
^{7}Be:
Phys. Lett. B658 (2008) 101
PRL 107 (2011) 141302

pep:
PRL 108 (2012) 051302

^{8}B:
Phys. Rev. D82 (2010) 033006

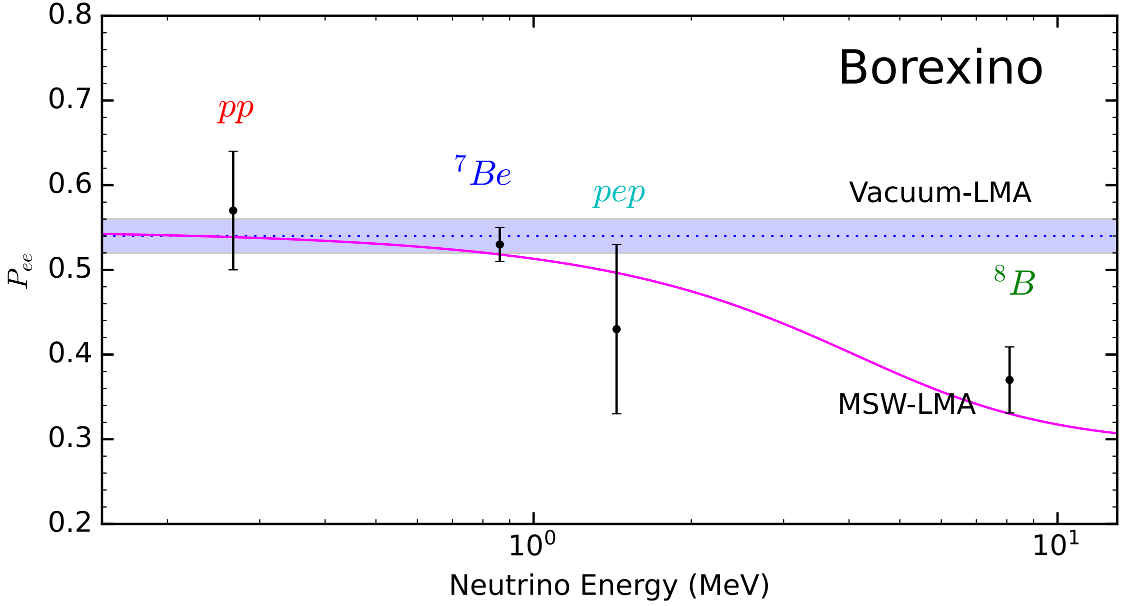
→ Error bars are large!

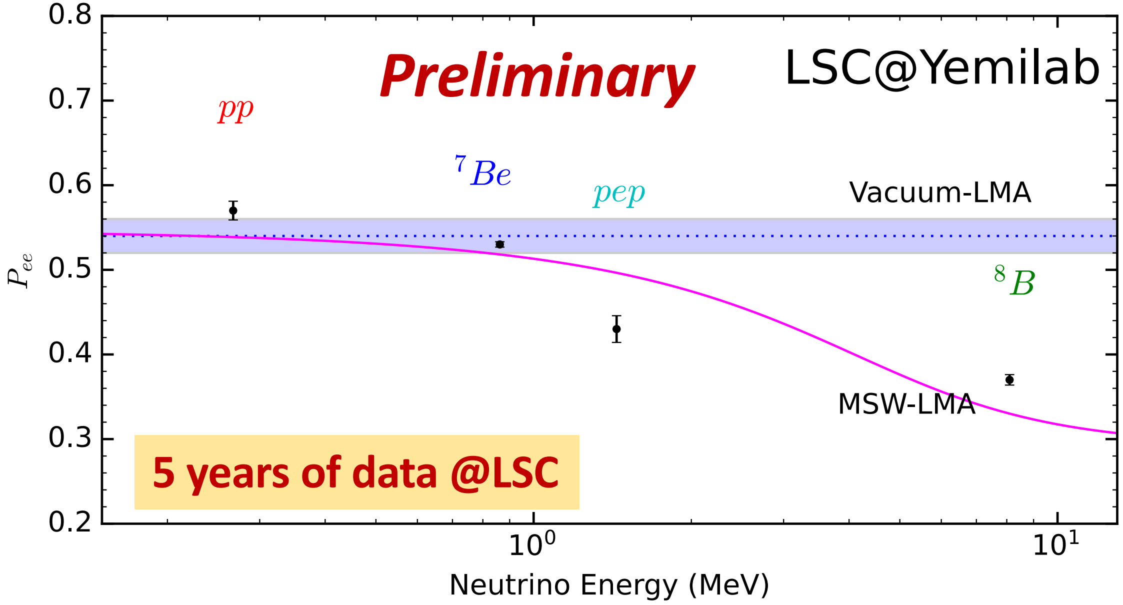
New Physics with Solar Neutrinos ?



→ We aim to reduce the error bars
with LSC detector “Bigger & Better” than Borexino.

Solar Neutrinos





Preliminary

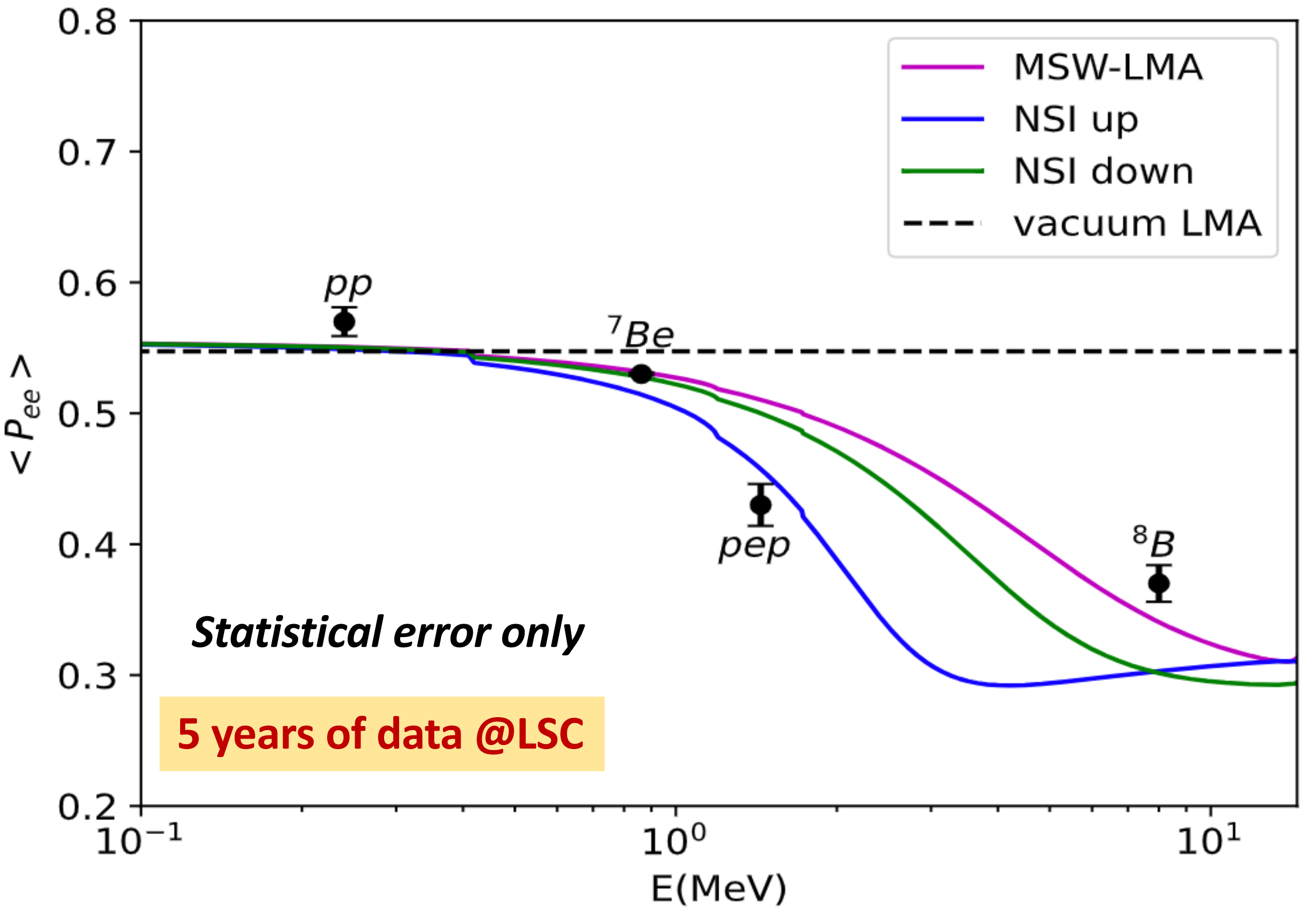
5 years of data @LSC

→ Shows Statistical Error Only.

Huge Reduction
of
Statistical Error!

Searching for BSM
would be possible!

If systematic uncertainties
are well in control.



Borexino-measured values are used with LSC statistical error.

Solar Metallicity (Z)

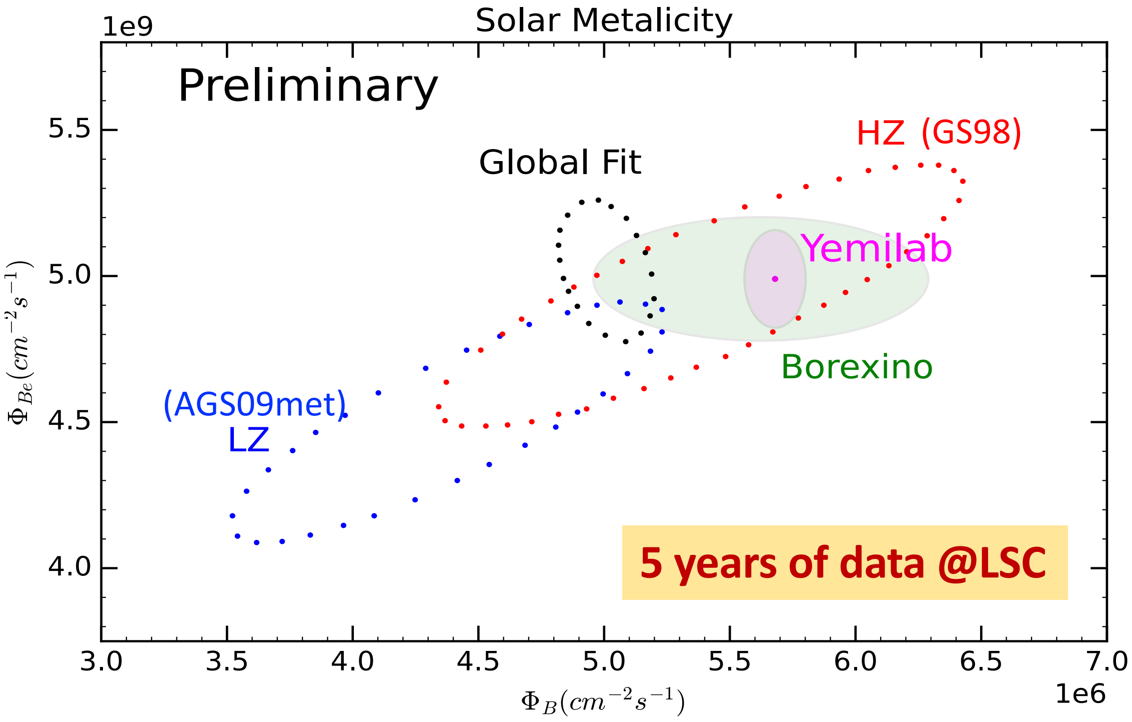
> "Even a very small fraction of metals is sufficient to alter the behavior of a star completely."

The mass abundance of **metals**
(all elements heavier than He)

- Impact the fate of a start:
  size, temperature, brightness, lifespan, etc.
- Solar metalicity becomes a standard for other stars' metalicity.

Year	1998	2009	2011	2021	2022
Model	GS98	AGS09met	Caffau11	AGG21	MB22
Z/X	0.023	0.018	0.0209	0.0187	0.0225
	HZ	LZ	LZ	LZ	HZ

	FLUX	Dependence on T	SSM-/HZ (1)	SSM-/LZ(2)	DIFF. (HZ-LZ)/HZ
pp chain	pp (10^{10} cm^{-2} s^{-1})	$T^{-0.9}$	5.98(1±0.006)	6.03(1±0.005)	-0.8%
	pep (10^{8} cm^{-2} s^{-1})	$T^{-1.4}$	1.44(1±0.01)	1.46(1±0.009)	-1.4%
	^{7}Be (10^{9} cm^{-2} s^{-1})	T^{11}	4.94(1±0.06)	4.50(1±0.06)	8.9%
	^{8}B (10^{6} cm^{-2} s^{-1})	T^{24}	5.46(1±0.12)	4.50(1±0.12)	17.6%
CNO cycle	^{13}N (10^{8} cm^{-2} s^{-1})	T^{18}	2.78(1±0.15)	2.04(1±0.14)	26.6%
	^{15}O (10^{8} cm^{-2} s^{-1})	T^{20}	2.05(1±0.17)	1.44(1±0.16)	29.7%



5 years of data @LSC

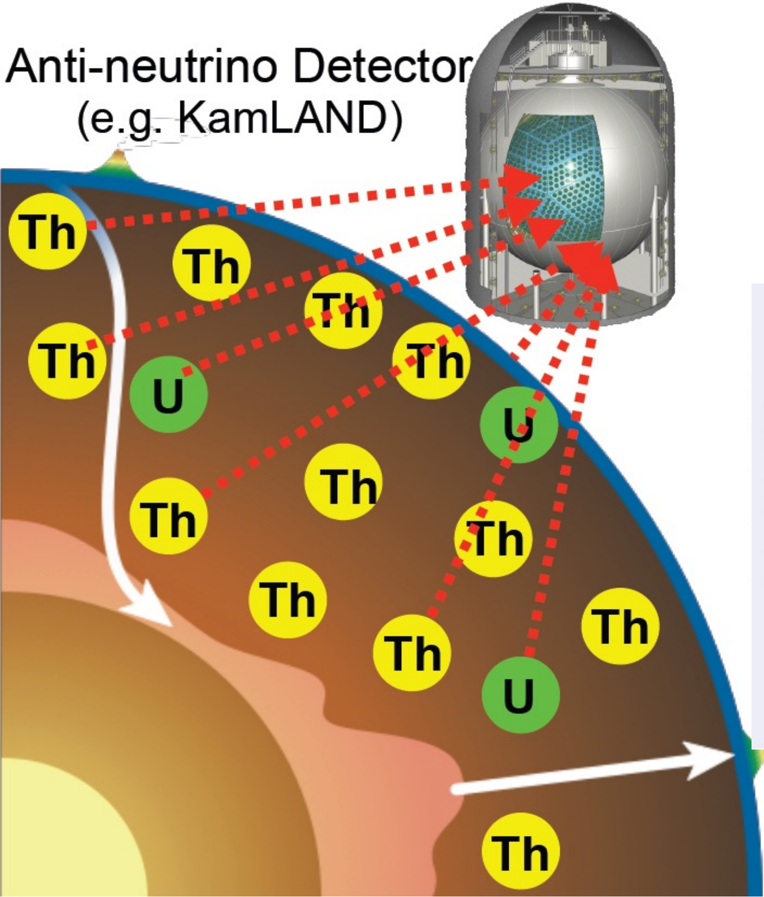
Geo Neutrinos

Electron-antineutrinos from natural radioactive decays

Watanabe
2021

$\bar{\nu}_e \;\; 4.1 \times 10^6/\mathrm{cm}^2/\mathrm{sec}$

Anti-neutrino Detector
(e.g. KamLAND)



β-decay

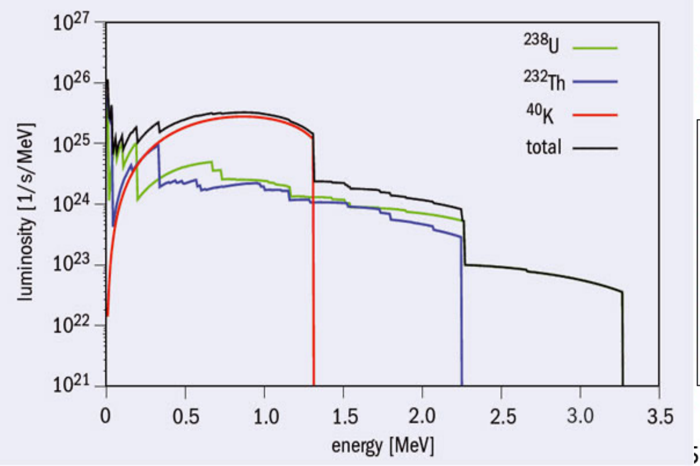
geo-neutrinos

$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\alpha + 6\mathrm{e}^- + 6\bar{\nu}_\mathrm{e} + 51.7\,\mathrm{MeV}$$

$$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\alpha + 4\mathrm{e}^- + 4\bar{\nu}_\mathrm{e} + 42.7\,\mathrm{MeV}$$

$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + \mathrm{e}^- + \bar{\nu}_\mathrm{e} + 1.311\,\mathrm{MeV}\,(89.28\%)$$

Energy threshold, 1.8 MeV



Antineutrino Energy [MeV]

inverse β-decay

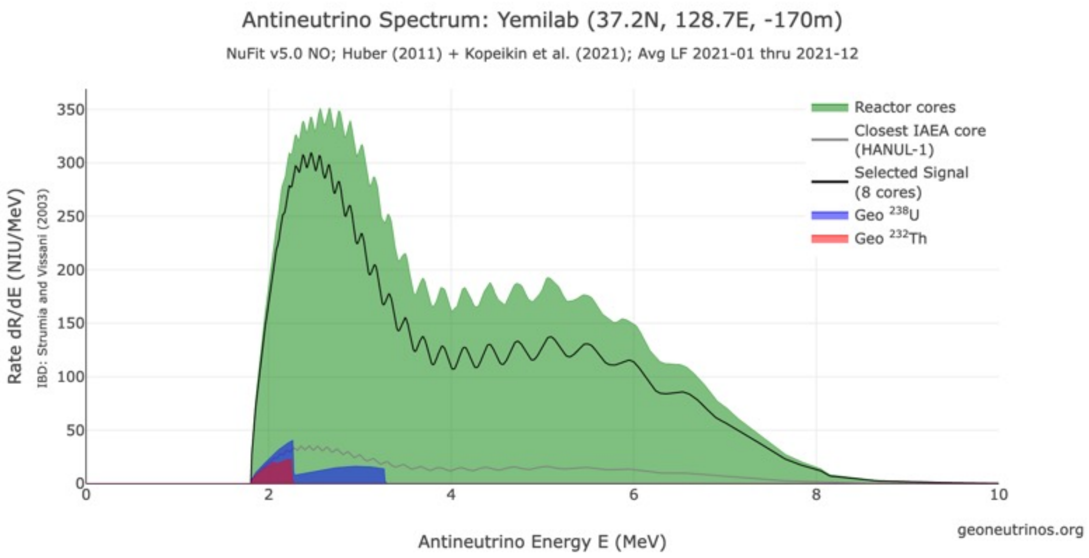
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- *Only geo-neutrinos from U and Th are detectable right now
- *^{40}K geo-neutrino detection needs another technology.

Number of geo $\bar{\nu}_e \propto$ amount of U Th, **radiogenic heat**

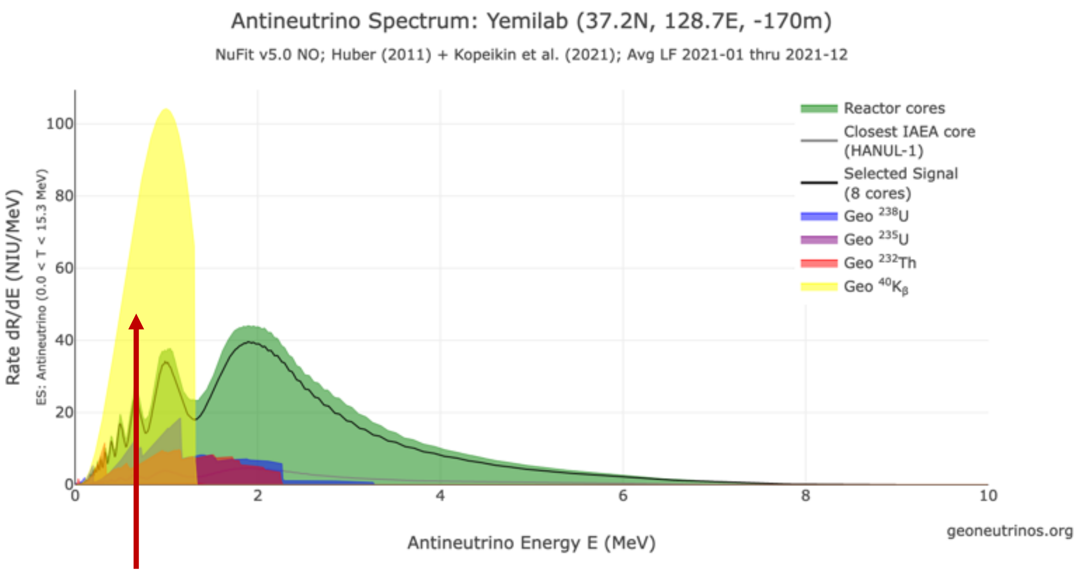
Geo & Reactor ν Estimations at LSC

IBD channel


Antineutrino Spectrum: Yemilab (37.2N, 128.7E, -170m)

NuFit v5.0 NO; Huber (2011) + Kopeikin et al. (2021); Avg LF 2021-01 thru 2021-12

ES channel


Antineutrino Spectrum: Yemilab (37.2N, 128.7E, -170m)

NuFit v5.0 NO; Huber (2011) + Kopeikin et al. (2021); Avg LF 2021-01 thru 2021-12

Geo-neutrinos: 60.6 ± 13.6 IBD/year
Reactor-neutrinos: 460 ~ 1500 IBD/year

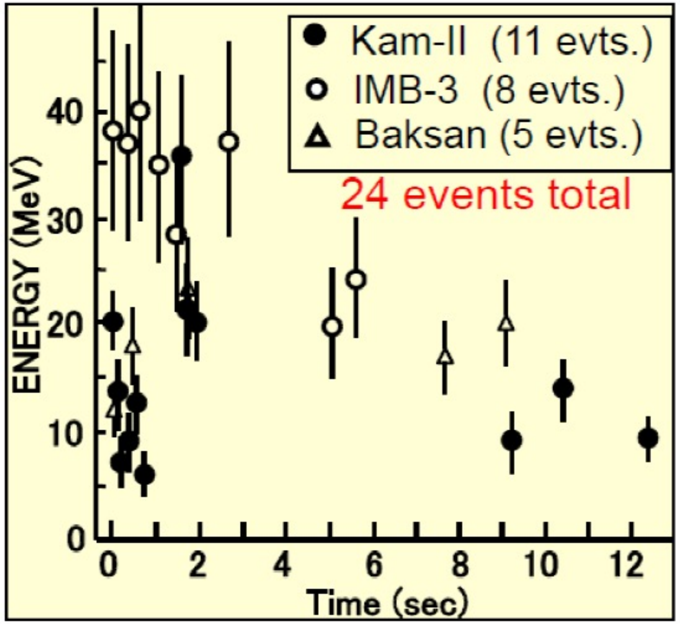
Geo-neutrinos are enhanced in this channel.

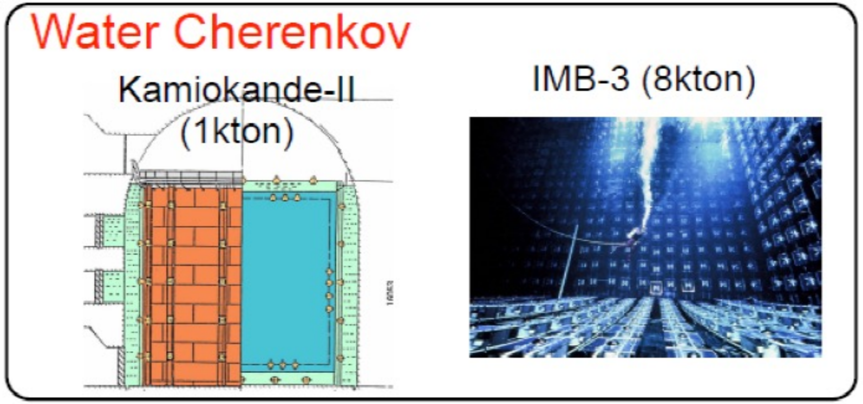
Solar ν background: ~x2

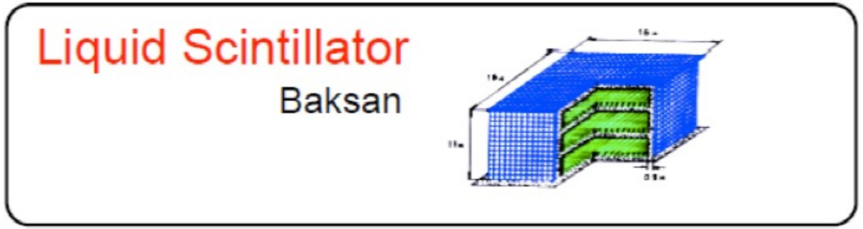
(→ Directionality will help to remove this bkg.)

SN 1987A @Large Magellanic Cloud

7:35 (UT), Feb. 23, 1987, at 50kpc







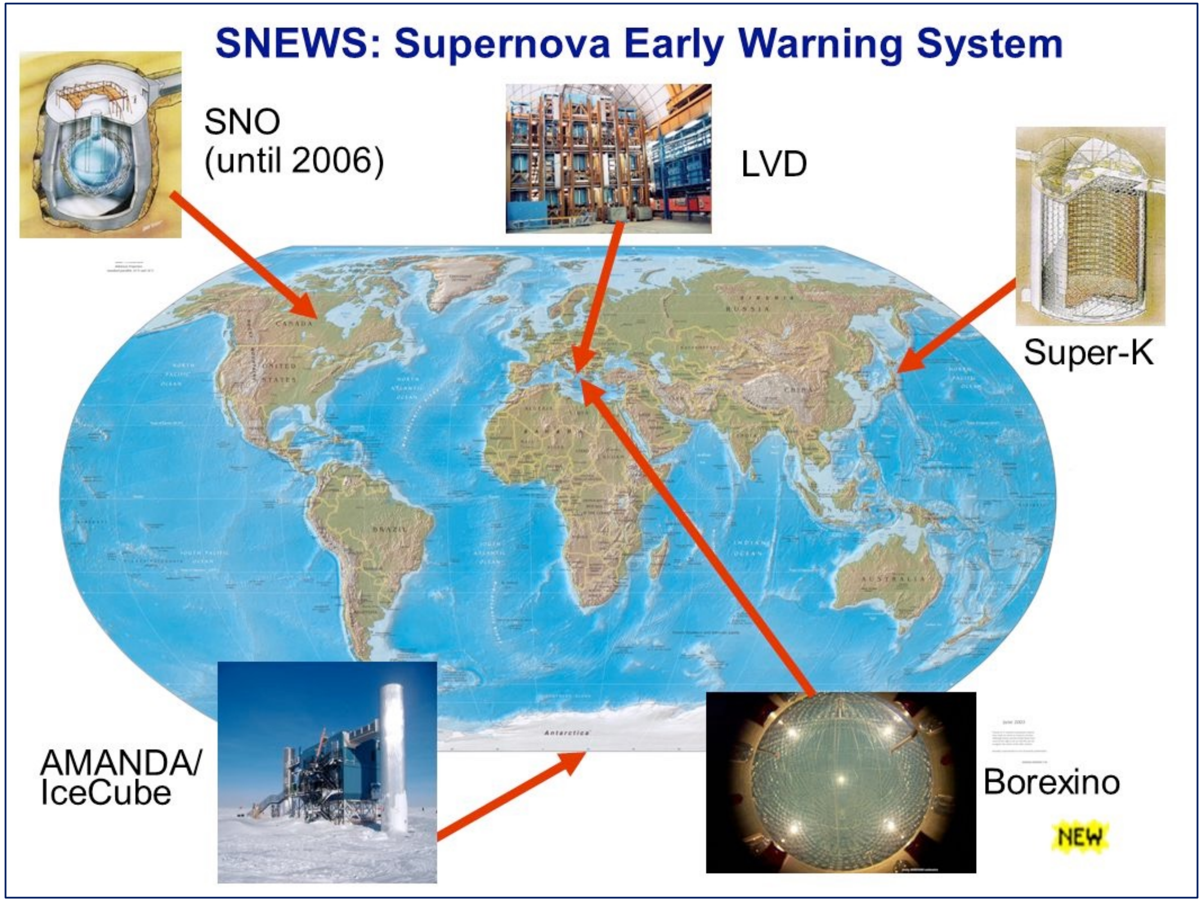
☐ Supernova Burst:

- ~10^{58} ν
- E_ν^{tot}: ~10^{53} erg
  → $\sim 99\%$ E_{burst}
- E_ν : 1 ~ 100 MeV

➢ **We need more precise measurement w/ more statistics.**

- ❖ Betelgeuse (at 131pc) could become a Supernova any time.

SNEWS 1.0



SNEWS 2.0

(Since 2019)

- SNν Community
- Astronomers (optical)
- GW Community

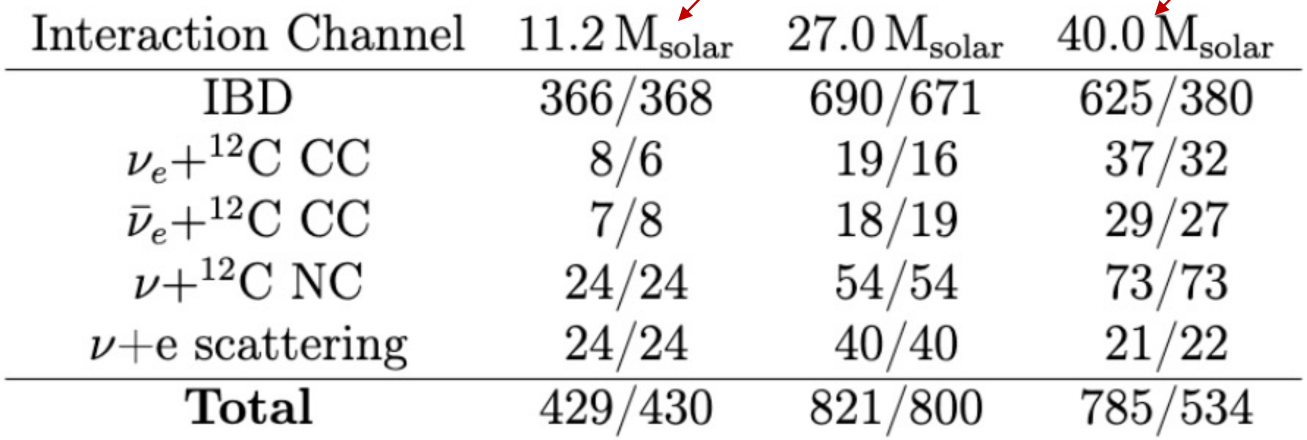
→ Multi-messenger

arXiv:2011.00035

Supernova Burst ν Estimations @ 10 kpc

Forming
Netron star

Forming
Blackhole



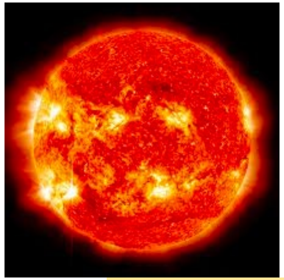
Interaction Channel	11.2 M_{solar}	27.0 M_{solar}	40.0 M_{solar}
IBD	366/368	690/671	625/380
ν_e+^{12}C CC	8/6	19/16	37/32
$\bar{\nu}_e$+^{12}C CC	7/8	18/19	29/27
ν+^{12}C NC	24/24	54/54	73/73
ν+e scattering	24/24	40/40	21/22
Total	429/430	821/800	785/534

NO / IO

- LSC is expected to observe 430~820 ν events from SN burst at 10 kpc.

Broad Physics Program

Solar ν



Supernova ν

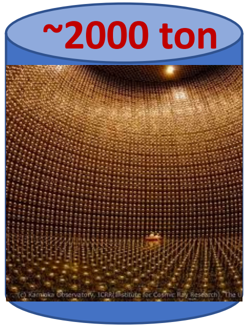
ν Telescope

Phase-II

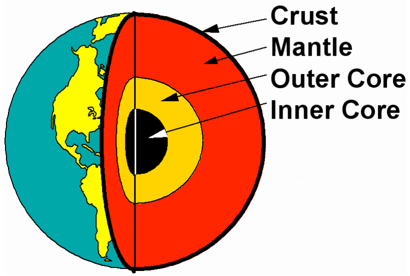
w/ linac

e- beam

Dark Photon

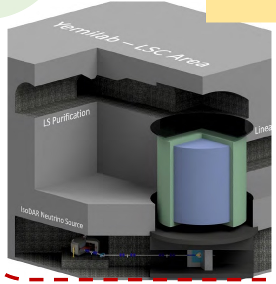


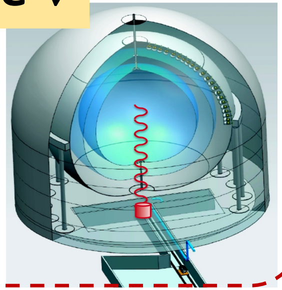
Geo ν



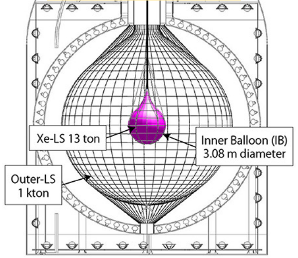
New step to Geo Science

Sterile ν





0νββ ?



Dark Photon (DP) ϕ, γ', A'

❖ DP is the simplest and most popular hypothetical particle in a dark sector.

- DP can mediate interaction w/ dark matter.
- DP itself can be a candidate of dark matter.
- DP can be searched via vector portal.

$$\boxed{\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{m_\phi^2}{2}A'_\mu A'^\mu}$$

DP field strength tensor

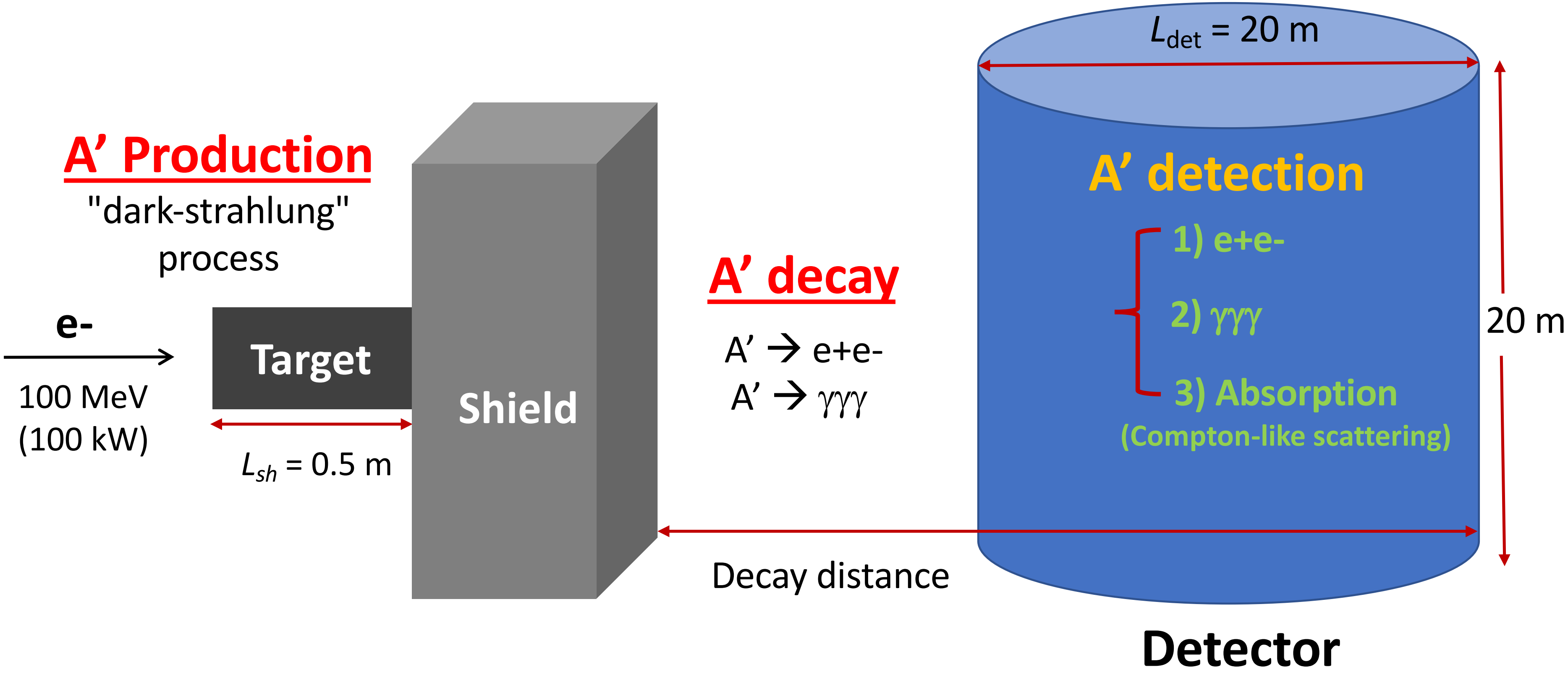
$U(1)_D$ gauge field

ε: "kinetic mixing" parameter

Dark Photon Search Scheme w/ LSC

- **DP search experiments at underground**

Izaguirre, Krnjaic, Pospelov, PRD 92, 095014 (2015)

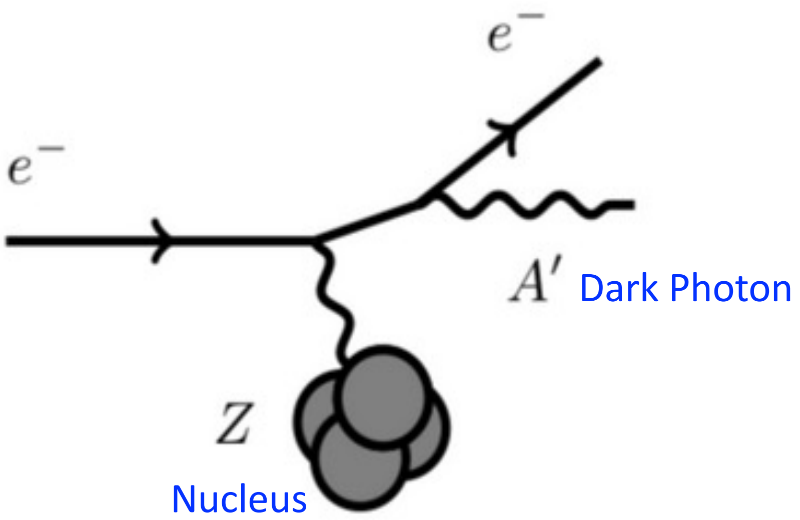


Dark Photon Production & Detection @Yemilab

e^- beam

"Bremsstrahlung-like" process

"Dark-strahlung"



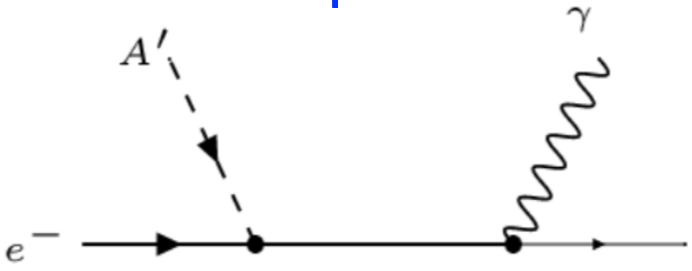
☐ Visible Decays

A' → e+ e- (> 1 MeV)

A' → $\gamma\gamma\gamma$ (< 1 MeV)

☐ Absorption

Compton-like



Expected # of Dark Photons

- ☐ **Production: "dark-strahlung"**
- ☐ **Detection : *A' → e+e- or 3γ, or A' absorption***

DP production x-section

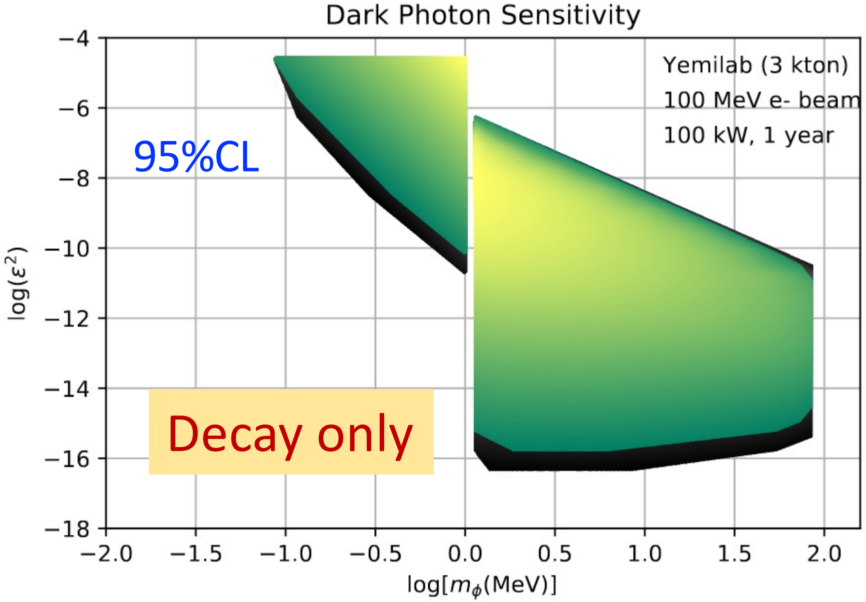
$$N_\phi \approx \frac{N_e X}{M}\int_{E_{\min}}^{E_0} dE \int_{x_{\min}}^{x_{\max}} \times dx \int_0^T dt I_e(E_0, E, t)\frac{d\sigma}{dx} e^{-L_{\rm sh}(\frac{1}{l_\phi}+\frac{1}{\lambda})}(\underbrace{1 - e^{-L_{\rm dec}/l_\phi}}_{\text{only decay signal}})$$

Liu & Miller: PRD 96, 016004 (2017)

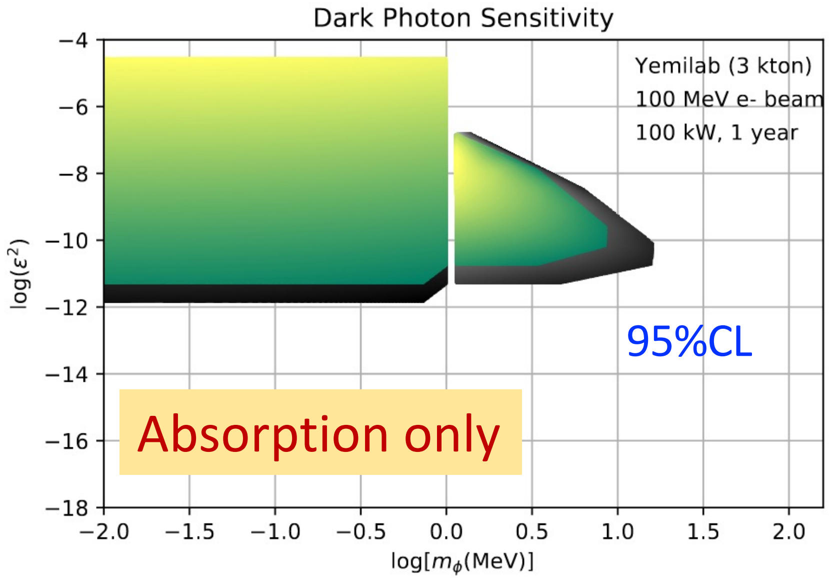
We should add an additional term of DP absorption signal to decay signal.

$$\underbrace{\text{x}[1 - \exp(- L_{dec}/l_\phi - L_{det}/\lambda_{det})]}_{\text{decay or absorption signal}}$$

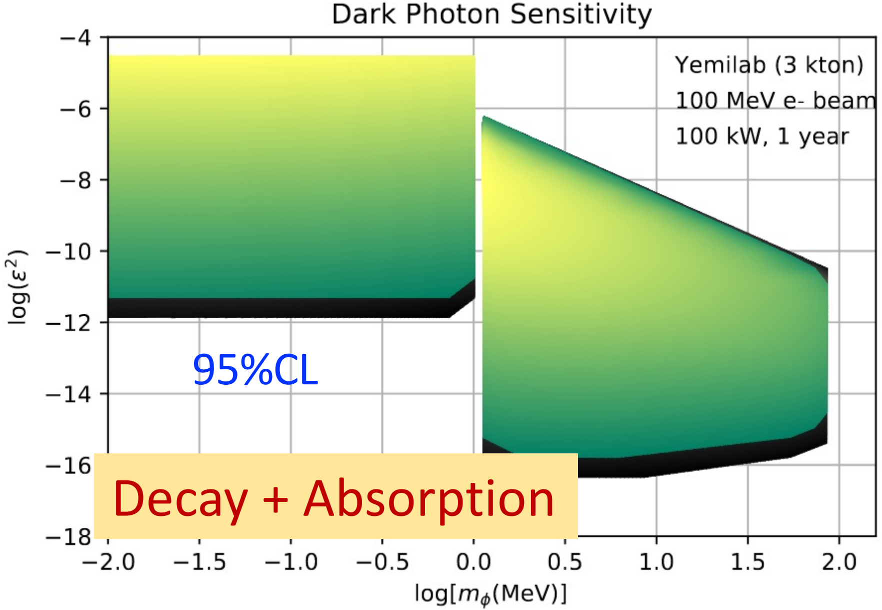
where,
L_{det}: detector length
λ_{det}: DP abs. length in detector



Decay only



Absorption only



Decay + Absorption

Rough Background Estimation

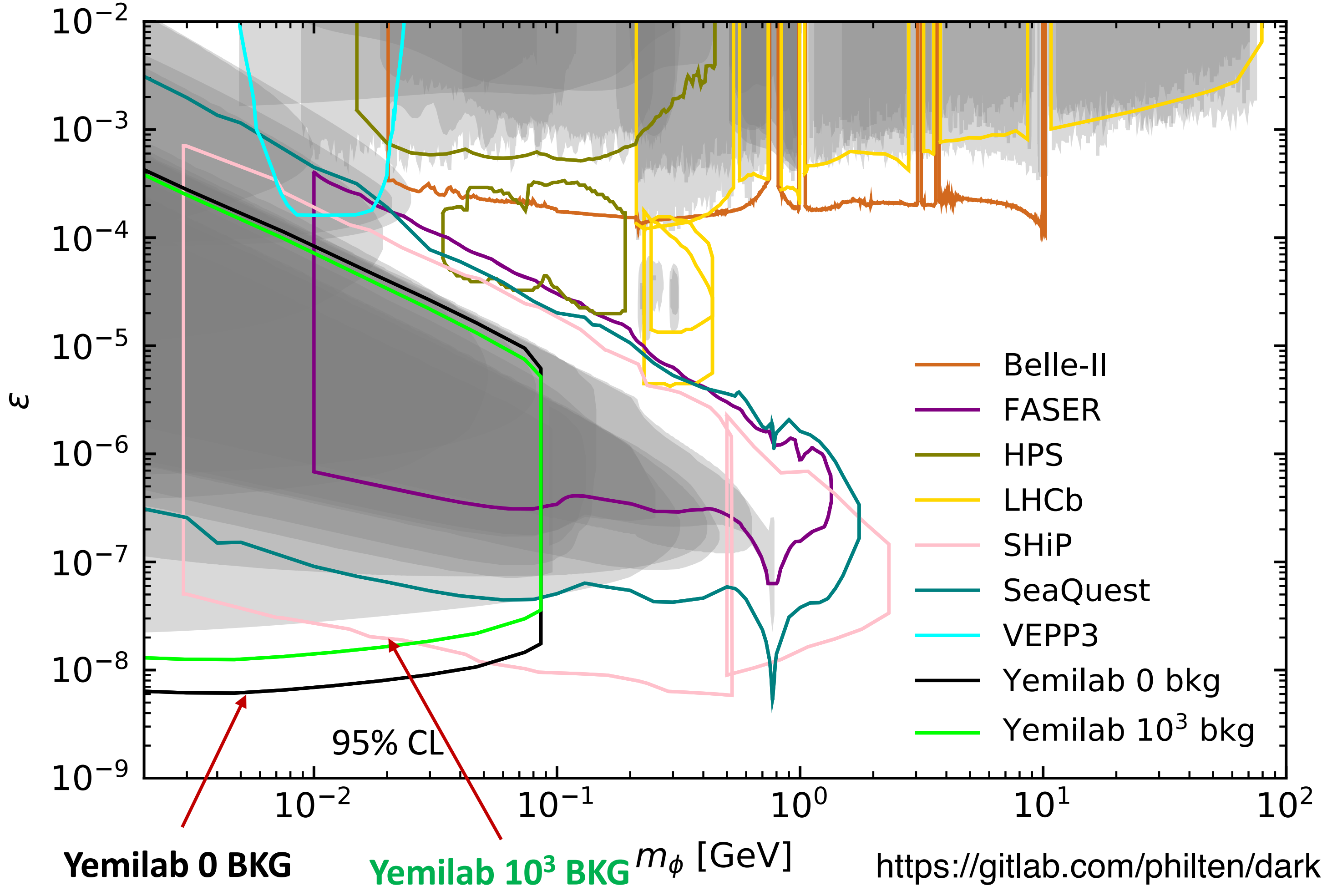
Signal = Beam (ON – OFF) data

→ # of background events in beam OFF data can affect our sensitivity

Background types	#. BKG events (/year/1 kton fiducial vol.)	Comments
Solar ν (^{8}B), residual, external BKG	935	Estimated from Borexino arXiv:1709.00756
Atmospheric ν	67	Estimated from Borexino *J.Phys.Conf.Ser.* 675 (2016) 1, 012014
Neutrons from beam	0	Block w/ rocks (few meters) & 5 MeV cut
ν (from e beam cc/nc) scattering	0	Negligible (10^{-10})
Total	1002	

Current Limits & Future Projections

S.H. Seo & Y.D. Kim
JHEP04(2021)135



https://gitlab.com/philten/darkcast

Best “direct” DP search sensitivity in $M_\phi < 30$ MeV (10^3 BKG)

$\gamma \rightarrow$ A' Oscillations (m_ϕ < 1 MeV)

1812.02719
1804.10777
1501.07292

- $\gamma \longrightarrow$ A' oscillation @ target (**T**ungsten)

$$P(\gamma \to A') = \epsilon^2 \times \frac{{m_\phi}^4}{(\Delta m^2)^2 + E_\gamma^2 \Gamma^2},$$

- A' $\longrightarrow \gamma$ oscillation @ detector (**W**ater)

$$P(A' \to \gamma) = \epsilon^2 \times \frac{{m_\phi}^4}{(\Delta m^2)^2 + E_\gamma^2 \Gamma^2} \times \Gamma L,$$

$$\text{where } \Delta m^2 = \sqrt{(m_\phi^2 - m_\gamma^2)^2 + 2\epsilon^2 m_\phi^2 (m_\phi^2 + m_\gamma^2)} \approx |m_\phi^2 - m_\gamma^2|, \; m_\gamma = \sqrt{4\pi\alpha n_e / m_e}$$

$$\boxed{P(\gamma \leftrightarrow A') = \epsilon^4 \times \frac{m_\phi^8}{\left((m_\phi^2 - m_\gamma^{\mathrm{T}\,2})^2 + E_\gamma^2 \Gamma_{\mathrm{T}}^2\right) \times \left((m_\phi^2 - m_\gamma^{\mathrm{W}\,2})^2 + E_\gamma^2 \Gamma_{\mathrm{W}}^2\right)} \times \Gamma_{\mathrm{W}} L,}$$

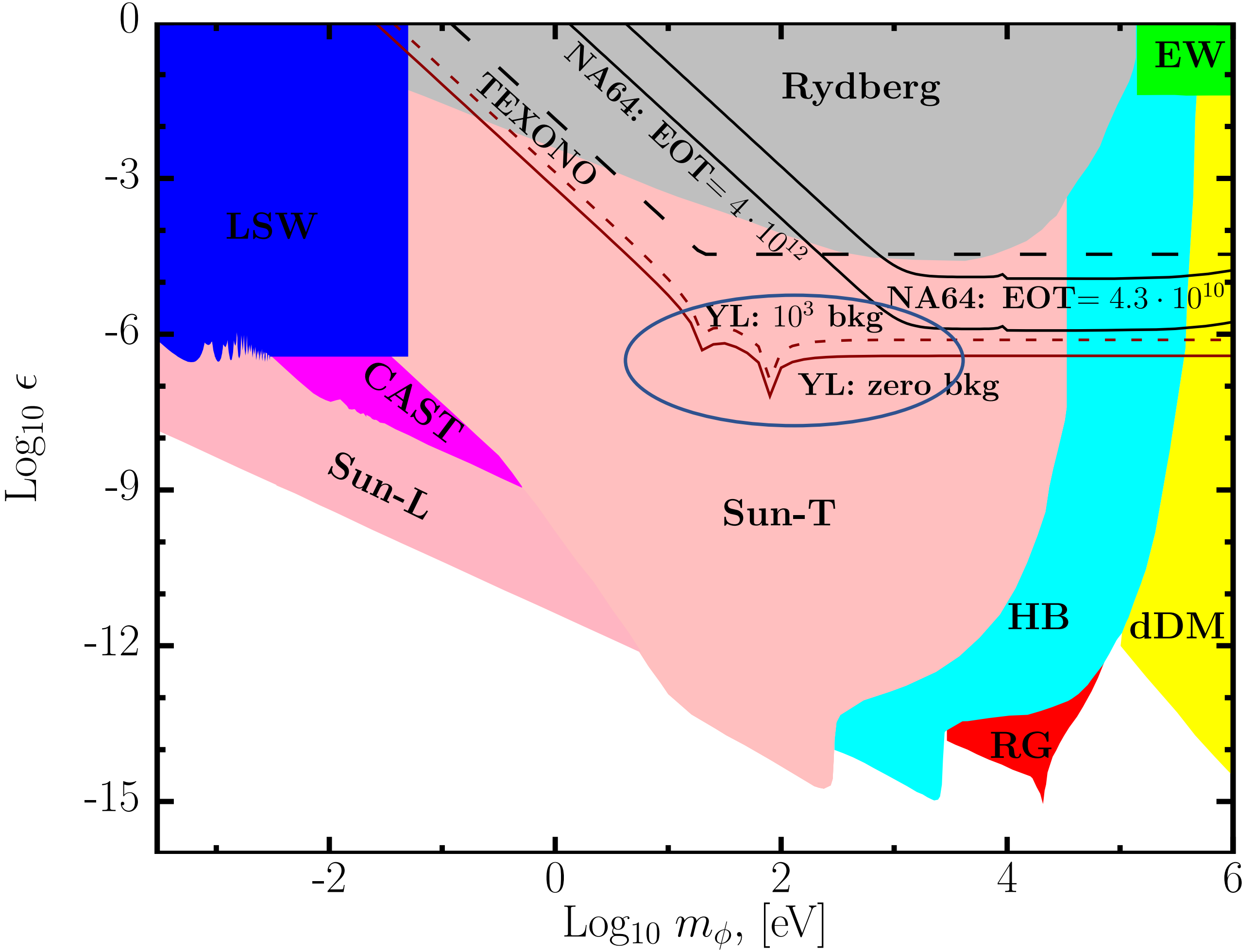
$$\boxed{N_\phi^{\mathrm{osc}} \approx N_{\mathrm{e}} \times \int_{E_\gamma^{\mathrm{min}}}^{E_\gamma^{\mathrm{max}}} dE_\gamma P(\gamma \leftrightarrow A') \int_0^T dt \left(I_\gamma^{(1)}(t, E_\gamma) + I_\gamma^{(2)}(t, E_\gamma) \right)}$$

Photon flux per electron

Tsai & Whitis, Phys.Rev. 149 (1966) 1248-1257

γ → A' Oscillation Sensitivity

S.H. Seo & Y.D. Kim
JHEP04(2021)135

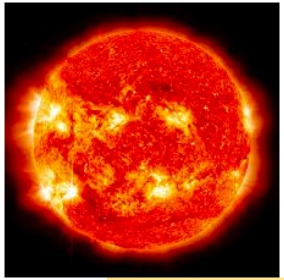


$m_\phi < 1$ **MeV**

Best **"direct"** DP search sensitivity at sub-MeV region

Broad Physics Program

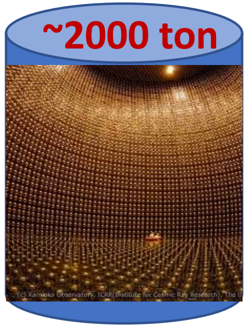
Solar ν



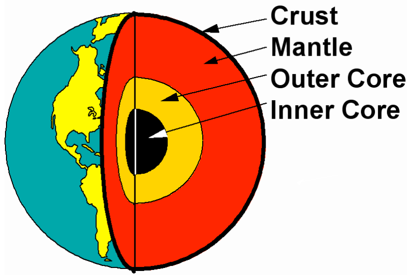
Supernova ν

ν Telescope

e- beam



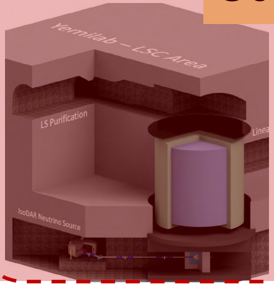
Geo ν

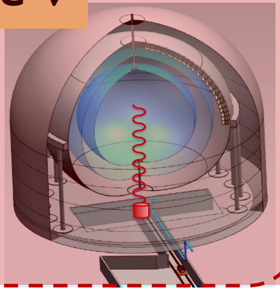


Dark Photon

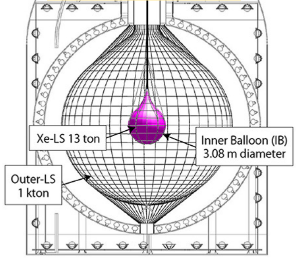
New step to Geo Science

Sterile ν





0νββ ?



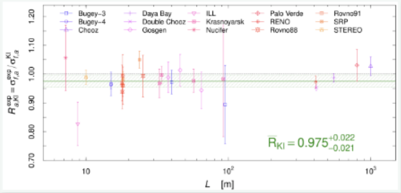
Phase-III

w/ IsoDAR

or Radio source

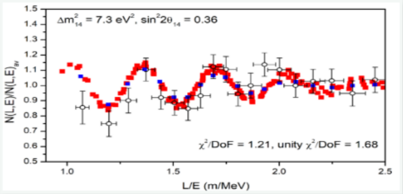
Short-Baseline Anomalies: Current Status

J. Kopp
@Nu2022



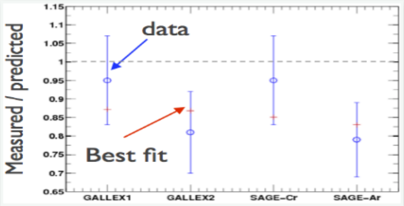
reactor flux anomaly
resolved with new input data
to flux calculation

✓



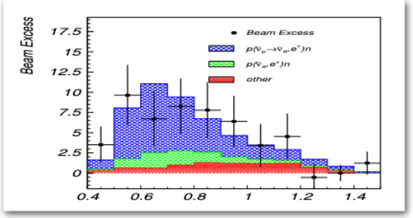
reactor spectra
is there really an anomaly?

?



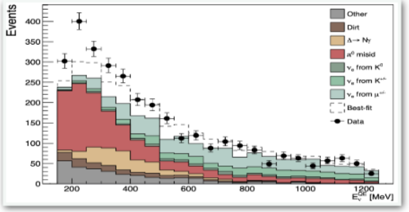
gallium anomaly
unresolved, recently reinforced

?



LSND
unresolved

?



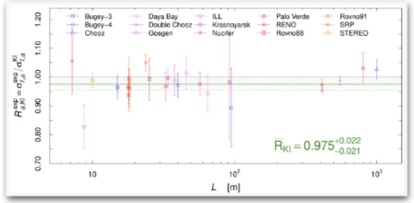
MiniBooNE
unresolved

?

Still
unresolved

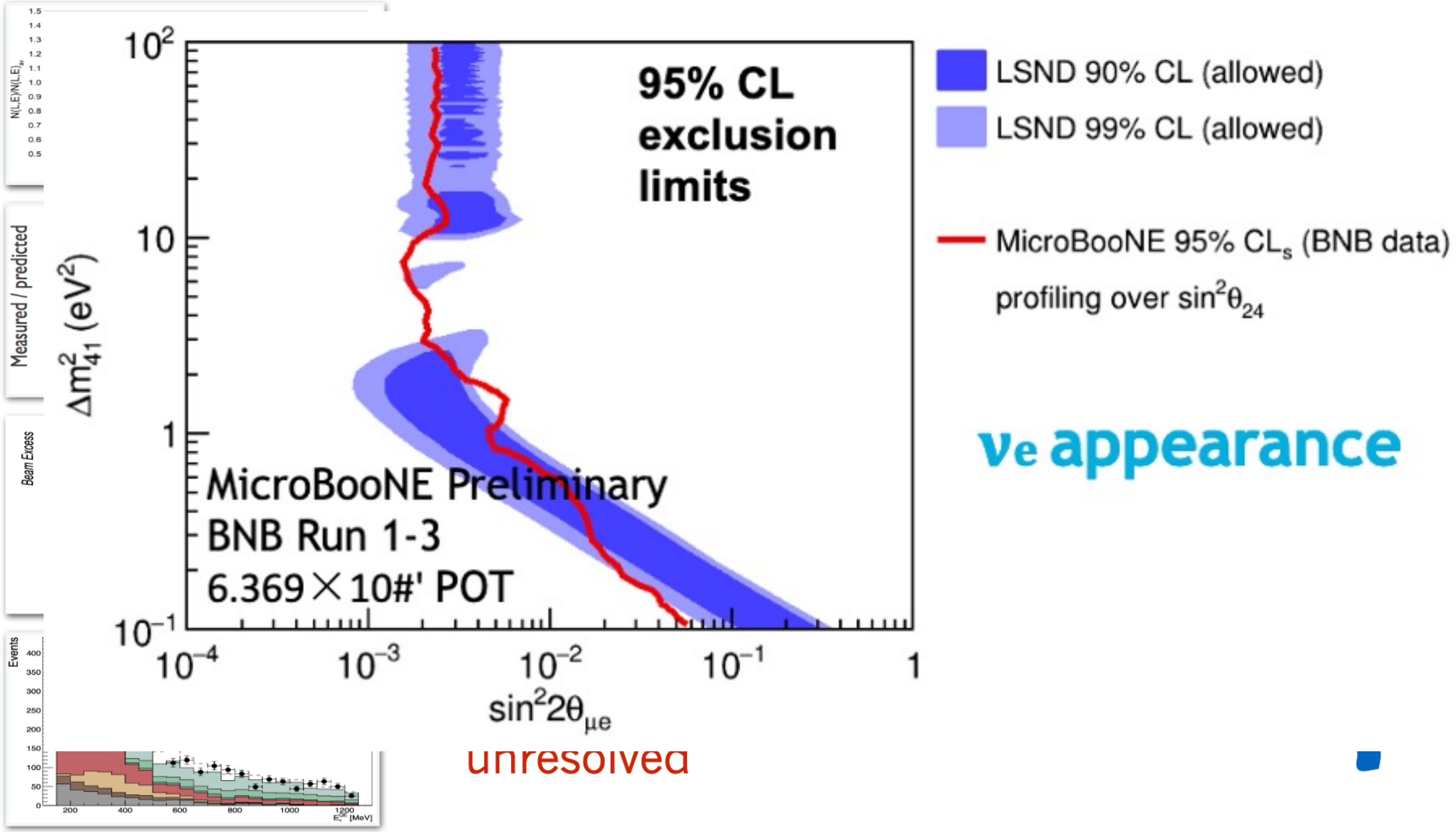
Short-Baseline Anomalies: Current Status

J. Kopp
@Nu2022



reactor flux anomaly
resolved with new input data
to flux calculation

✓



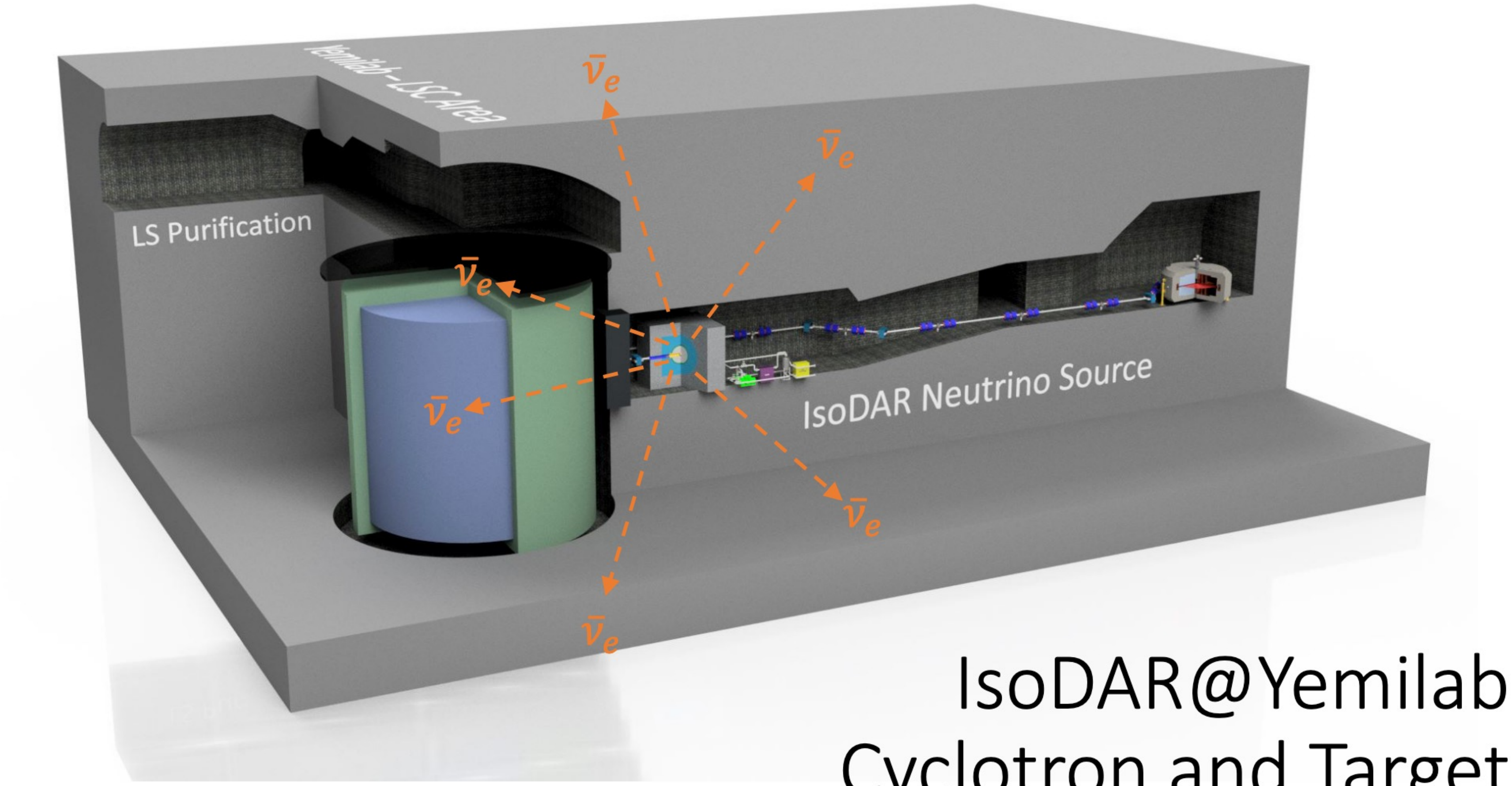
νe appearance

Still unresolved

[1] Sterile neutrino search with IsoDAR @Yemilab

Isotope **D**ecay **A**t **R**est

→ This method has never been tried!



IsoDAR@Yemilab
Cyclotron and Target

Publications:

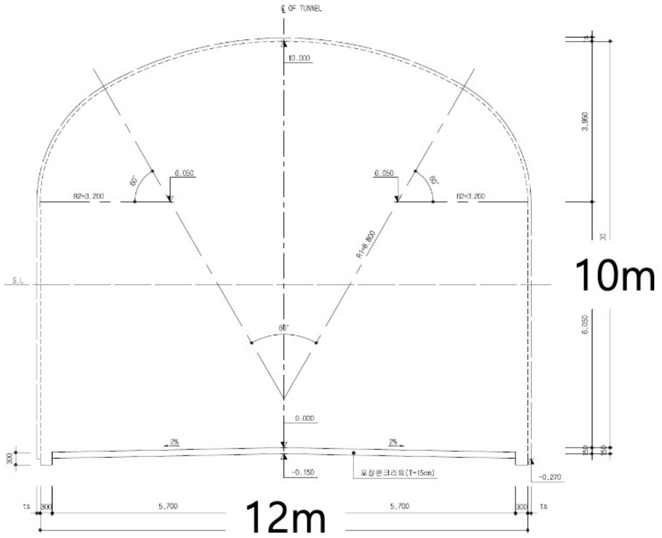
* arXiv:2111.09480
(**PRD**.105.052009)

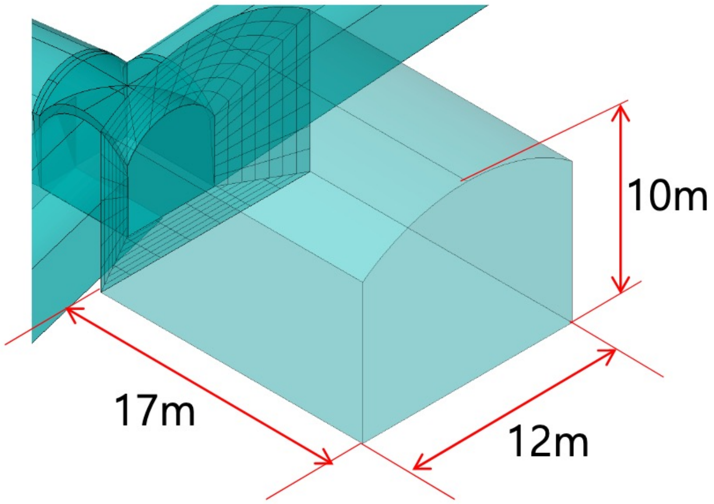
* arXiv:2201.10040
(submitted to **JINST**)

* arXiv:2110.10635

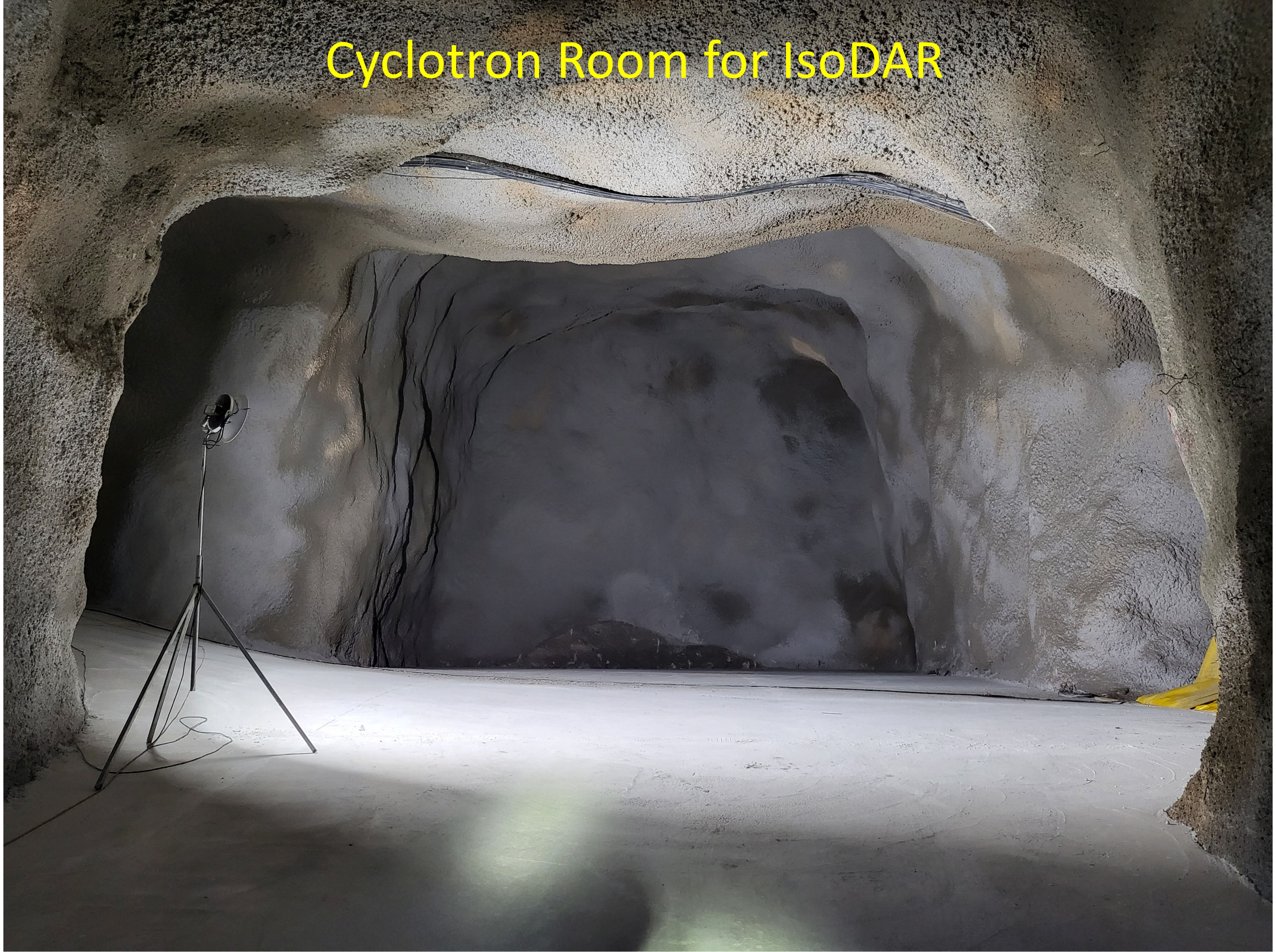
❖ Cyclotron Room

12 x 10 Tunnel



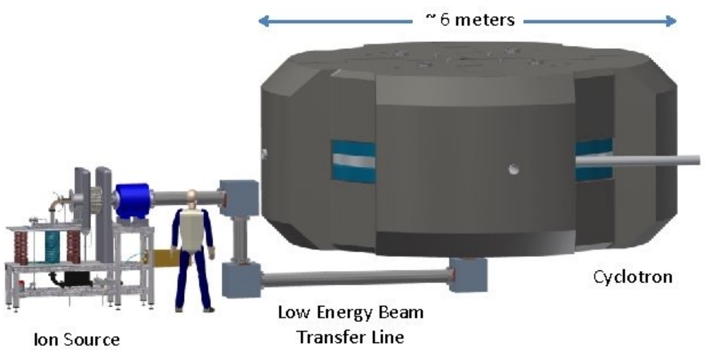


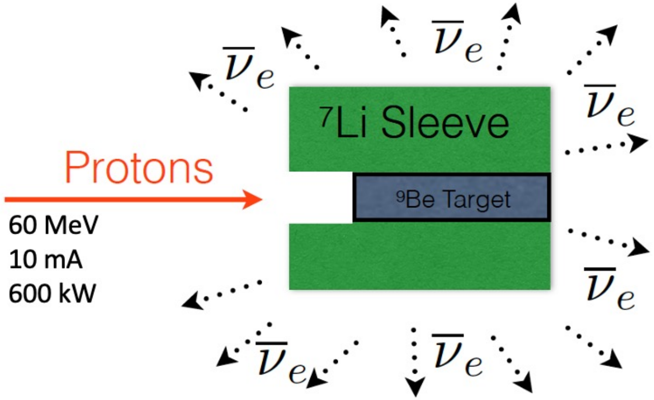
Cyclotron Room for IsoDAR

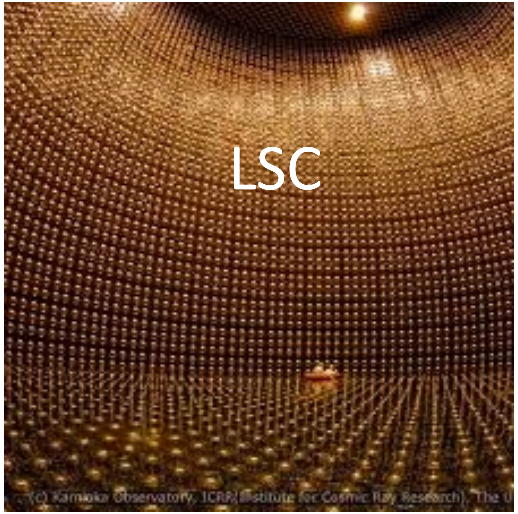


❑ Sterile ν search w/ IsoDAR@Yemilab

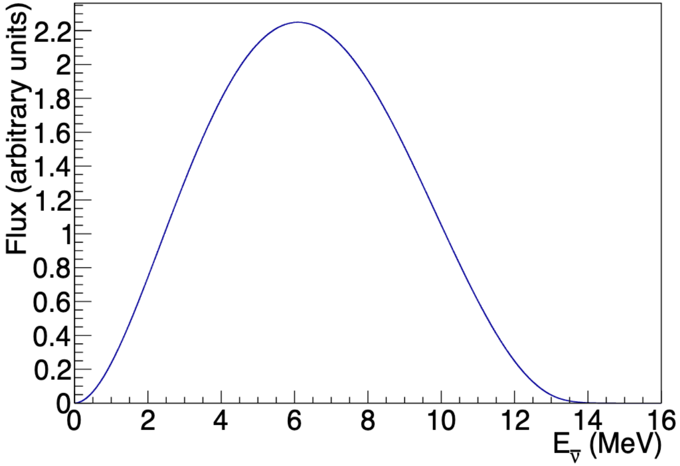
The IsoDAR Cyclotron and Ion Source







IsoDAR $\overline{\nu}$ spectrum



(1) $p + {}^9\mathrm{Be} \rightarrow {}^8\mathrm{Li} + 2p$

$p + {}^9\mathrm{Be} \rightarrow {}^9\mathrm{B} + n$

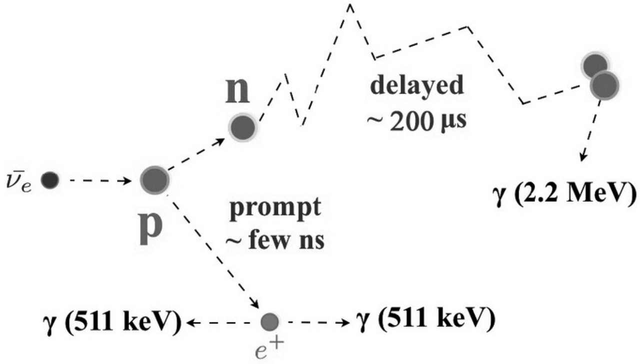
(2) $n + {}^7\mathrm{Li} \rightarrow {}^8\mathrm{Li} + \gamma$

$${}^8\mathrm{Li} \rightarrow {}^8\mathrm{Be} + e^- + \overline{\nu}_e$$

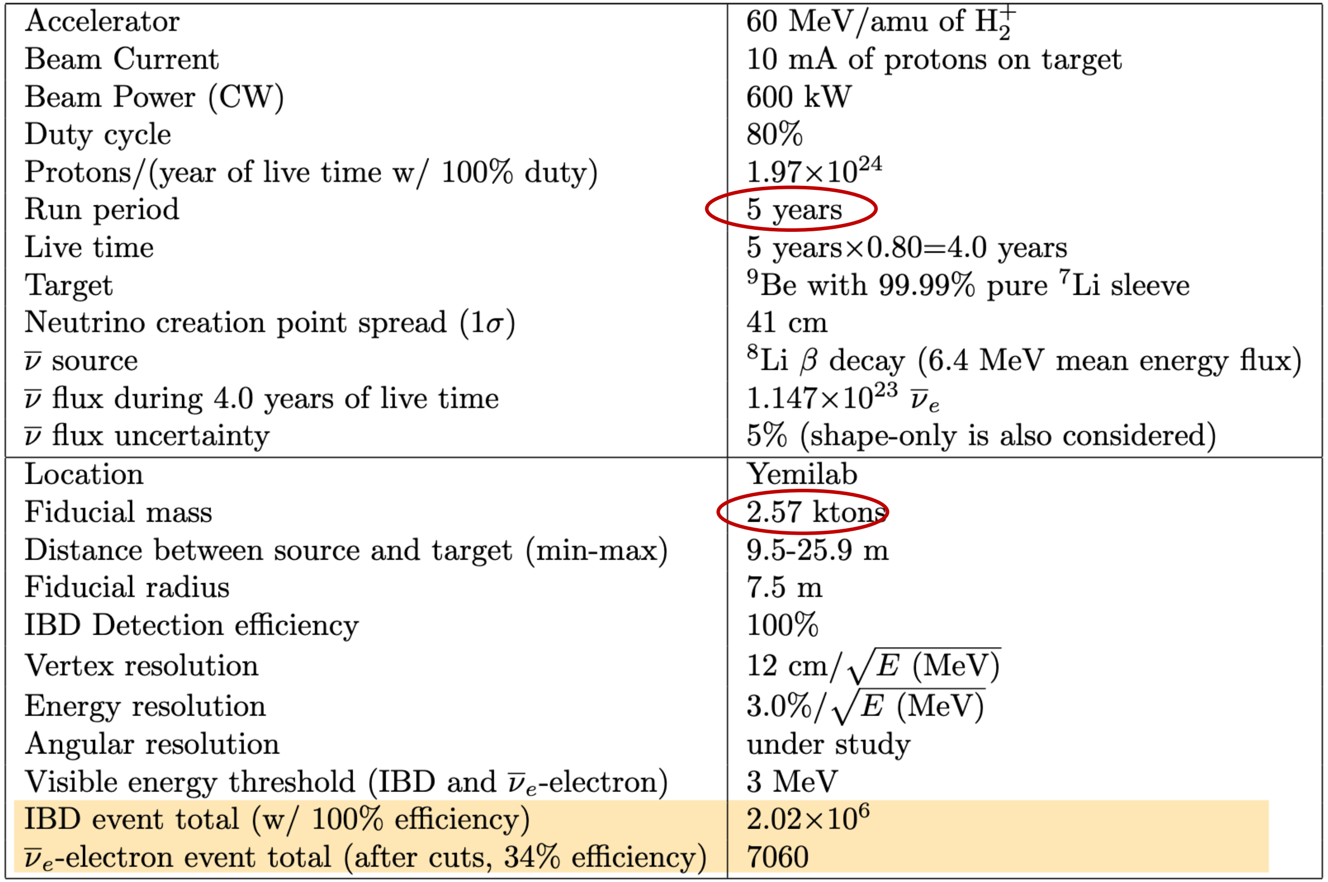
$\tau_{1/2}({}^8\mathrm{Li})$ ~ 0.84 sec

IBD interaction

$$p^+ + \overline{\nu}_e \rightarrow e^+ + n^0$$



IsoDAR@Yemilab Performance



Accelerator	60 MeV/amu of H_2^+
Beam Current	10 mA of protons on target
Beam Power (CW)	600 kW
Duty cycle	80%
Protons/(year of live time w/ 100% duty)	1.97×10^{24}
Run period	5 years
Live time	5 years×0.80=4.0 years
Target	^{9}Be with 99.99% pure ^{7}Li sleeve
Neutrino creation point spread (1σ)	41 cm
$\overline{\nu}$ source	^{8}Li β decay (6.4 MeV mean energy flux)
$\overline{\nu}$ flux during 4.0 years of live time	1.147×10^{23} $\overline{\nu}_e$
$\overline{\nu}$ flux uncertainty	5% (shape-only is also considered)
Location	Yemilab
Fiducial mass	2.57 ktons
Distance between source and target (min-max)	9.5-25.9 m
Fiducial radius	7.5 m
IBD Detection efficiency	100%
Vertex resolution	12 cm/$\sqrt{E}$ (MeV)
Energy resolution	3.0%/$\sqrt{E}$ (MeV)
Angular resolution	under study
Visible energy threshold (IBD and $\overline{\nu}_e$-electron)	3 MeV
IBD event total (w/ 100% efficiency)	2.02×10^6
$\overline{\nu}_e$-electron event total (after cuts, 34% efficiency)	7060

2 M IBD events/5 yrs

~7000 ES events/5yrs

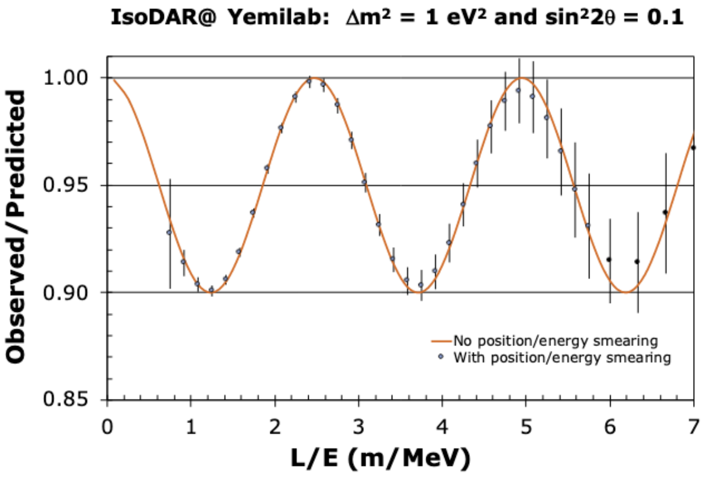
"Detector at Yemilab" assumptions are basically consistent with "KamLAND—897 tons, but bigger (and with the *possibility* of directional reconstruction)"

Sterile ν Search w/ IsoDAR@Yemilab

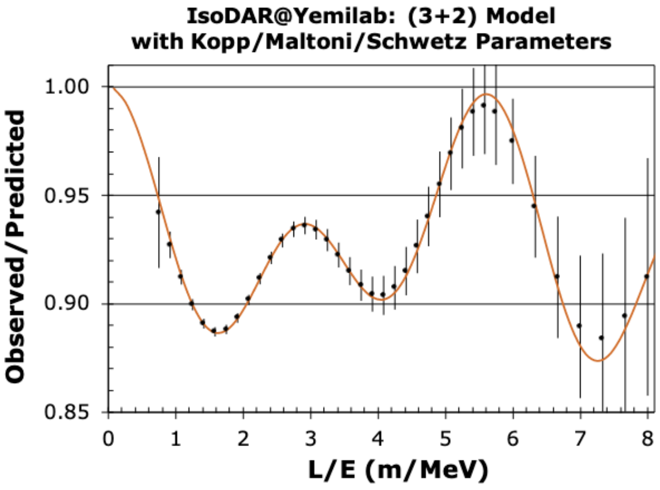
Possible Models & Signatures

arXiv:2111.09480
PRD 105 (2022) 5, 052009

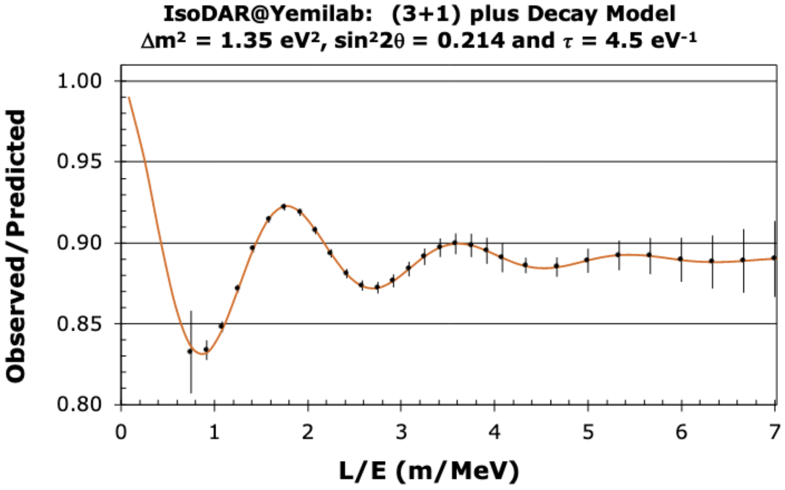
(3+1) ν



(3+2) ν



(3+1) ν + ν_s decay



→ IsoDAR@Yemilab can well distinguish different new physics models.

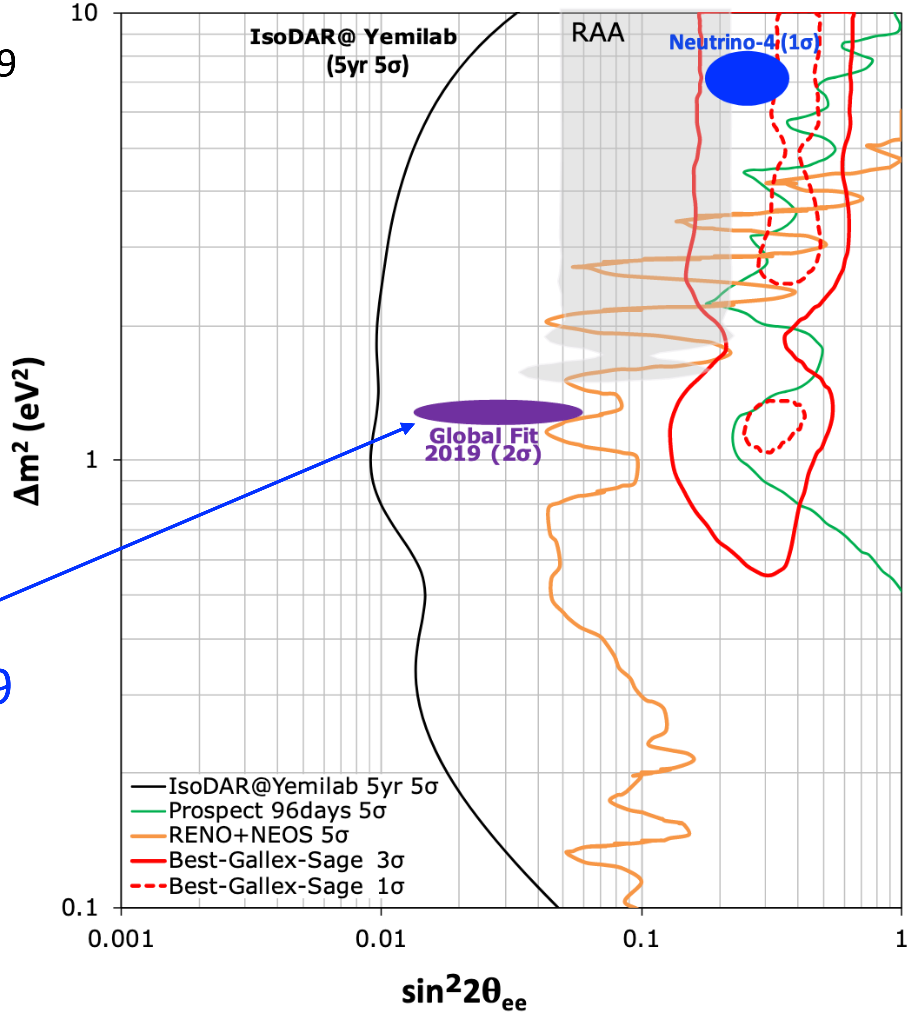
- The (3+1)+decay model significantly reduces the tension between appearance and disappearance experiments, improving the global-data goodness-of-fit.

1910.13456

Sterile neutrino search Sensitivity

IsoDAR @Yemilab P($\overline{\nu}_e \rightarrow \overline{\nu}_e$)

arXiv:2111.09480
PRD 105 (2022) 5, 052009



Global Fit 2019

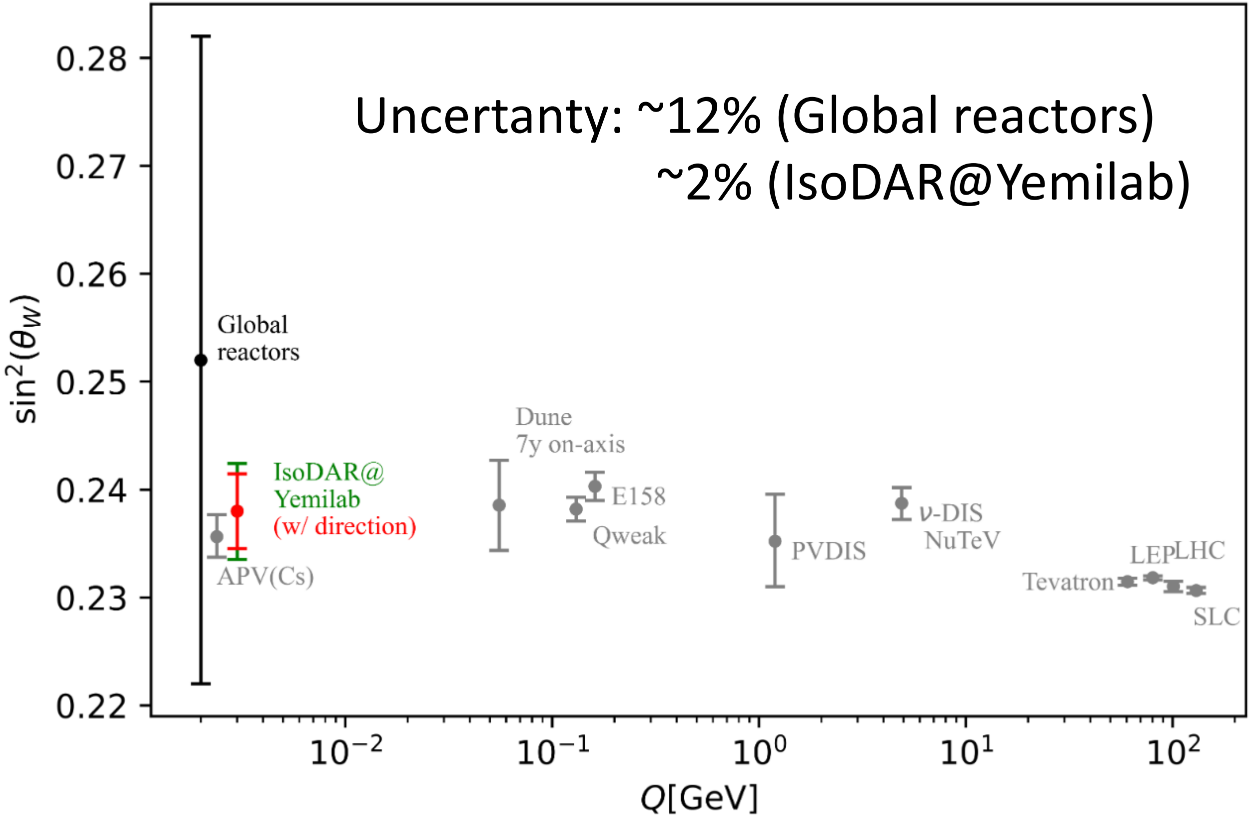
- World-leading result
- Definite conclusion on (3+1) ν or not

Advantage:
Unlike reactor/accelerator ν, IsoDAR has very well defined ν flux and shape.

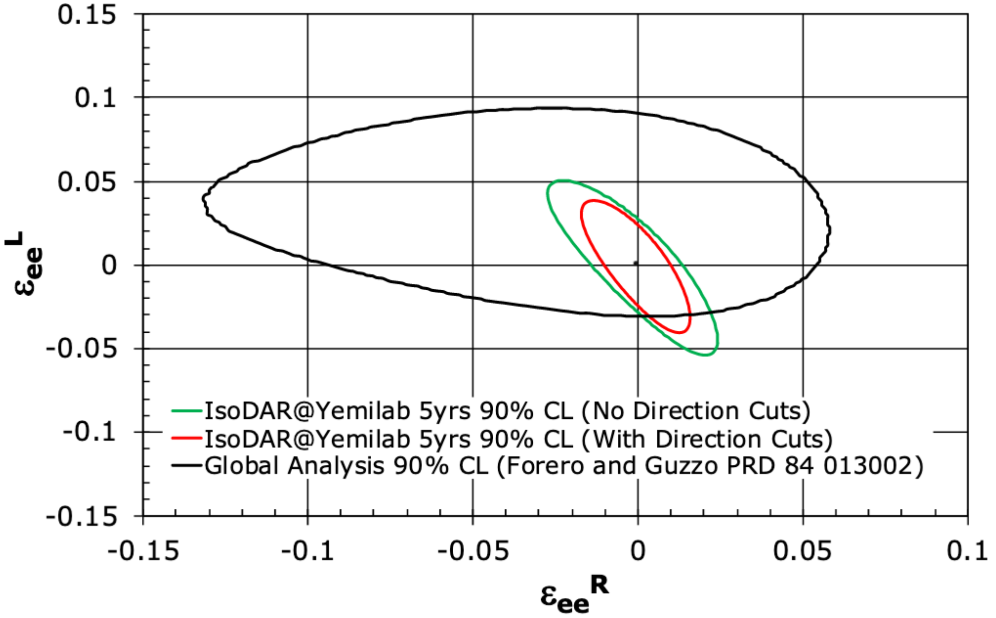
IsoDAR@Yemilab Elastic Scattering Events

arXiv:2111.09480
PRD 105 (2022) 5, 052009

Weak mixing angle θ_W measurement assuming standard ν interaction



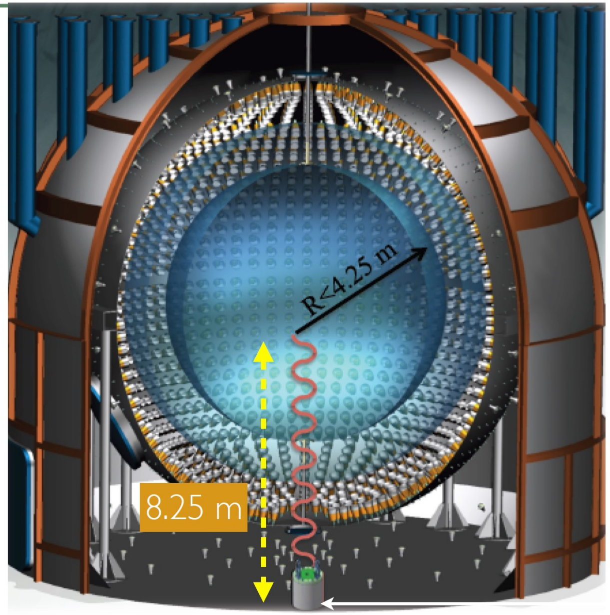
NSI



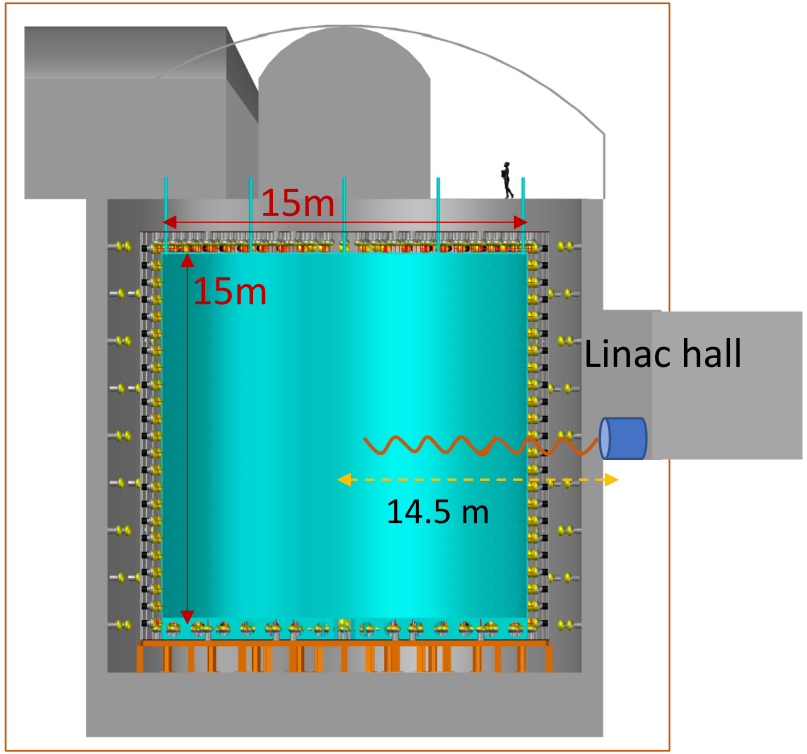
[2] Sterile ν search w/ radioactive sources

$P(\nu_e \rightarrow \nu_e)$

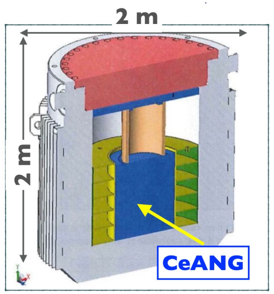
The Borexino detector and SOX



Useful data: distance range 4 - 12.25 m
(Yemilab will be better)



Distance range: 7 – 22 m



Source inside shield

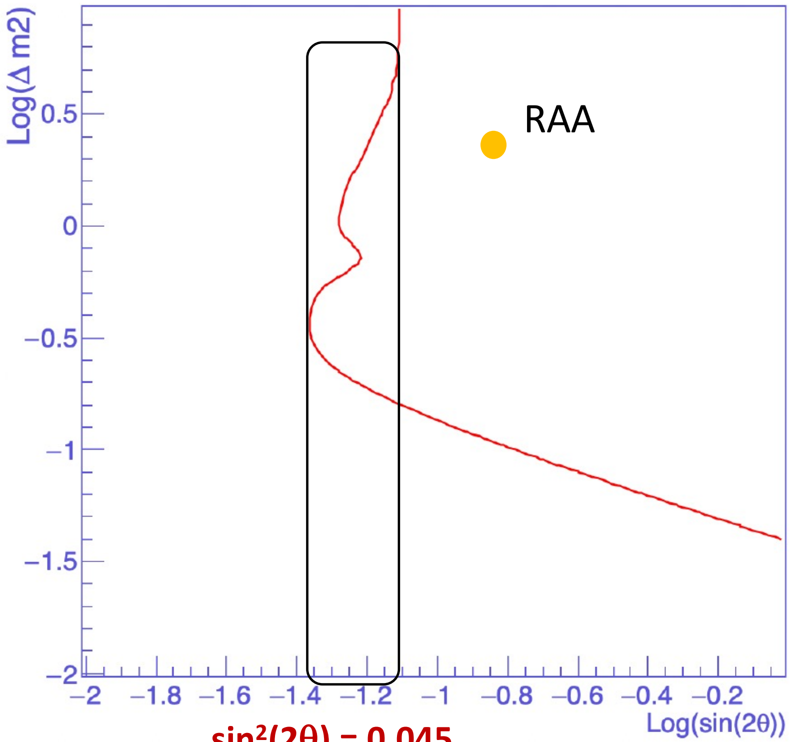
LSC @Yemilab

[2] Sterile ν Search Sensitivity w/ Radio-Source

Radio-active source

$P(\nu_e \rightarrow \nu_e)$

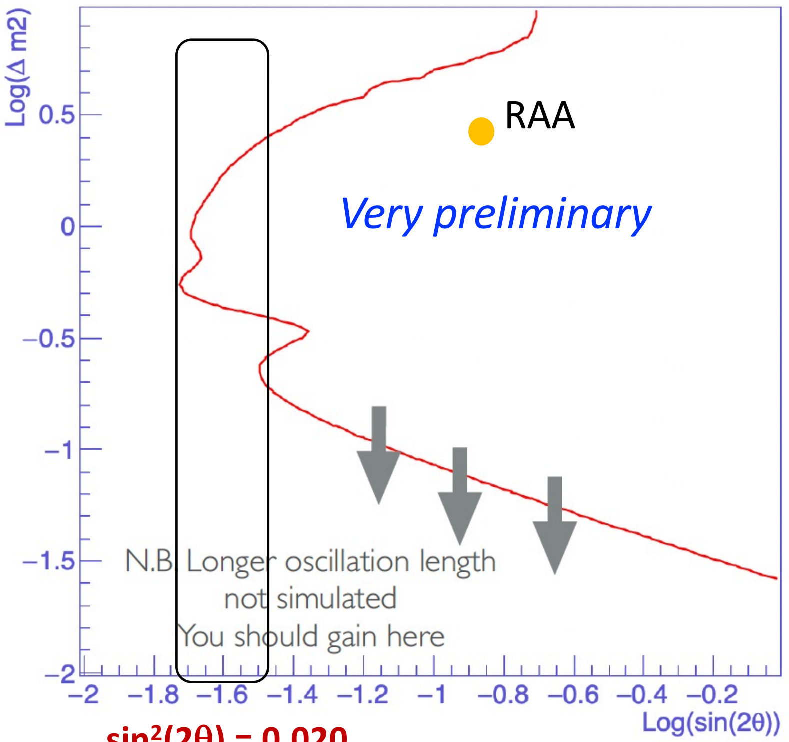
SOX original



$\sin^2(2\theta) = 0.045$

Ce-144 100 kCi

Yemilab



Very preliminary

$\sin^2(2\theta) = 0.020$

Ce-144 100 kCi

M. Pallavicini
Seminar @CUP-IBS

Rough Timeline

LSC @Yemilab

Design, R&D

Construction

Data Taking

→ 2024 → 2028 →

Still need funding for the LSC detector.

The construction depedns on when we get the funding.

Summary

☐ In the new Yemilab, a **cavern** for ν detector (~2.3 kton LS target) was prepared.

→ multi-purpose detector: **Solar/G**eo/SN ν, **dark photon, sterile** ν, etc.

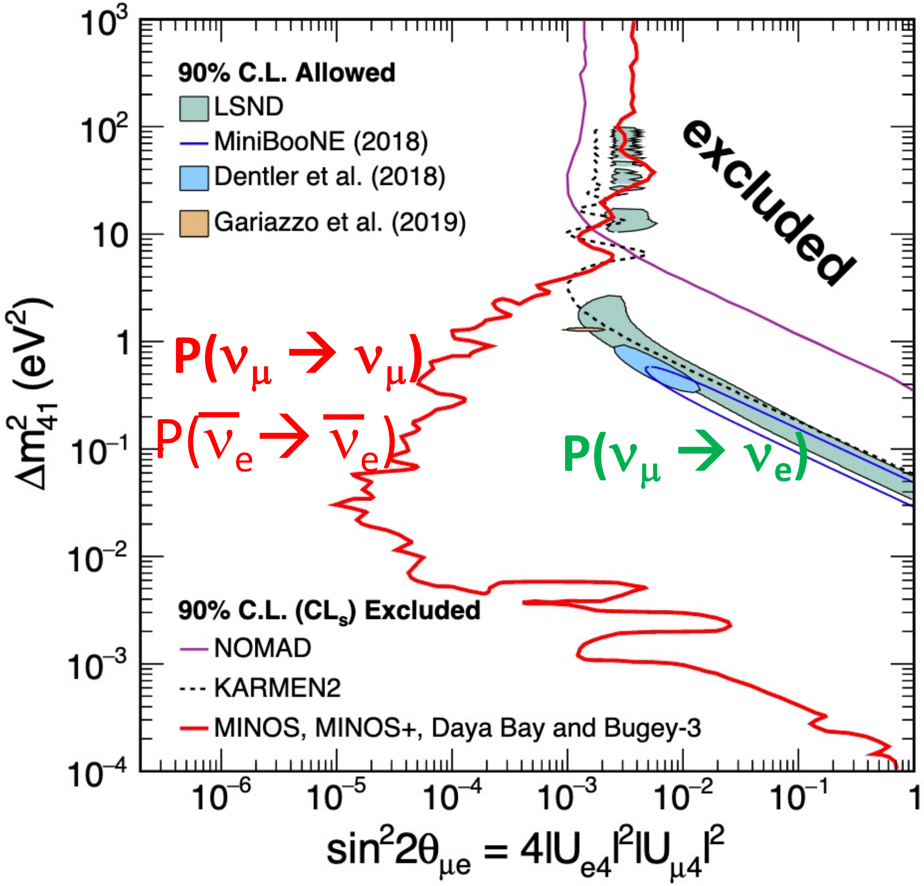
☐ Best measurements on solar ν flux might be possible.

☐ 1 year operation of 100 MeV-100 kW e^- beam ($2x10^{23}$ EOT):

→ **best "direct" dark photon search sensitivity**

in O(1 eV) $< M_\phi <$ 30 MeV (assuming 10^3 bkg events/year)

☐ IsoDAR@Yemilab: best sensitivity for sterile ν search in $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ channel. Can test different new physics models.


PRL 125, 071801 (2020)

- Some disagreements between MiniBooNE & MicroBooNE
- The tension between appearance and disappearance channels

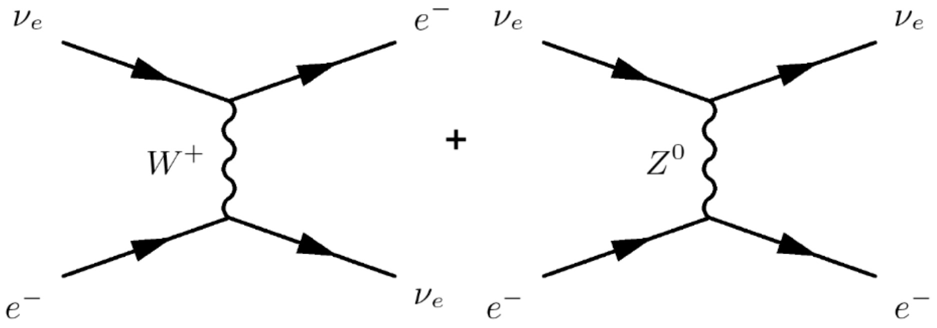
→ Need a more complex sterile ν model ?

(if new physics is indeed the source of the anomalous results)

➢ IsoDAR@Yemilab can test more complex sterile ν model.

❑ New physics search w/ IsoDAR@Yemilab

ES; $\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$



$$\boxed{\frac{d\sigma}{dT} = \frac{2G_F^2 m_e}{\pi}\left[g_R^2 + g_L^2\left(1-\frac{T}{E_\nu}\right)^2 - g_R g_L \frac{m_e T}{E_\nu^2}\right]}$$

$$g_R = \tfrac{1}{2}(g_V - g_A),\ g_L = \tfrac{1}{2}(g_V + g_A)$$

$$\boxed{g_L = \frac{1}{2} + \sin^2\theta_W, \quad g_R = \sin^2\theta_W}$$

$$[\sin^2 2\theta_W = (4\pi\alpha)/(\sqrt{2}G_F M_Z^2)]$$

NSI's alter the Standard Model couplings:

$$\bar{g}_R \equiv g_R^e + \varepsilon_{ee}^{eR}, \qquad \bar{g}_L \equiv 1 + g_L^e + \varepsilon_{ee}^{eL}$$

$$\sigma(\varepsilon_{ee}^{eR}, \varepsilon_{ee}^{eL}) = \frac{2m_e G_F^2 E_\nu}{\pi}\left(\bar{g}_L^2 + \frac{1}{3}\bar{g}_R^2\right).$$

(Continued…)

e- spectrum at *t* radiation length in beam target

$$I_e(E_0, E, t) = \frac{\left(\ln \frac{E_0}{E}\right)^{bt-1}}{E_0 \Gamma(bt)},$$

(b = 4/3 for vector particle)

Thick target approximation
(Tsai, 1974)